Feasibility Study for the Manufacturing of a Shock Absorber Using 3D Printing Technology

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A thesis submitted in partial fulfillment of requirements for the degree of Master of Engineering (Automation and Manufacturing Systems)

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Declaration

I certify that the work in this Capstone Project does not incorporate, without acknowledgement, any material previously submitted for a degree or diploma in any university. It does not contain any material previously published or written by another person except where due reference is made in the text.

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Date:

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Table of Contents

Declaration i

Acknowledgements ii

List of Figures v

List of Tables vii

Abstract viii

1. Chapter 1 Introduction 1

1.1. History of 3D printing 2

1.1. 3D Printing Processes and Technologies 6

1.1.1. Binder Jetting 7

1.1.2. Material Jetting 7

1.1.3. Direct Energy Deposition 8

1.1.4. Powder Bed Fusion 9

1.1.5. Sheet Lamination 12

1.1.6. Light Photopolymerization 13

1.1.7. Extrusion 14

1.2. Uses and Applications 15

1.3. Examples 16

1.4. Potential Impact 22

2. Chapter 2 FDM Technology 25

2.1. Desktop FDM Styles 25

2.2. Materials 27

2.2.1. Traditional 28

2.2.2. Dissolvable: 29

2.2.3. Exotics: 30

2.2.4. Others: 33

2.3. Shock Absorbers: 35

3. Chapter 3 Design and Develop 37

3.1. 3D Printer Up Plus 2 37

3.2. Designing for 3D printing 39

3.2.1. 45 degree rule: 39

3.2.2. Design to avoid support material 40

3.2.3. Know your printers limitations 40

3.2.4. Fit tolerances for Interlocking Parts 40
3.2.5. Improve thread width 41
3.2.6. Orient for the best resolution 41
3.2.7. Orient for stress 41
3.3. Design of the Spring Shock Absorber 41
3.4. Design of components 44
3.4.1. Design of spring 44
3.4.2. Design of cylinder 45
3.4.3. Design of piston, lock ring and preload adjuster 47
3.4.4. Design of caps 48
3.4.5. Design of Cam and Follower 49
4. Chapter 4: 3D Printing 52
4.4. Process 52
4.5. Printing with ABS 54
4.6. Printing with TPE 57
4.7. Single Print 61
5. Chapter 5 Tests and Results 64
5.4. Spring Rate 64
5.5. Costs and Time 66
5.6. Surface Treatment 67
5.6.1. Process 68
5.7. Functionality 71
6. Chapter 6 Summary and Conclusions 73
7. Appendix 76
8. References 91

List of Figures

Figure 1: Stereo Lithography Technology (Zent, 2013) 3
Figure 2: Fuse Deposition Modeling Technology (Junction, 2013) 4
Figure 3: The RepRap first version "Darwin" ('RepRap' n.d) 5
Figure 4: 3D print process flow (Cotteleer et al., 2013) 6
Figure 5: Binder Jetting (THRE3D, 2014) 7
Figure 6: Material Jetting (THRE3D, 2014) 8
Figure 7: Electro Beam Direct Manufacturing (THRE3D, 2014) 8
Figure 8: Ion Fusion Formation (THRE3D, 2014) 9
Figure 9: Laser Powder Forming (THRE3D, 2014) 9
Figure 10: Direct Metal Laser Sintering (THRE3D, 2014) 10
Figure 11: Electron Beam Melting (THRE3D, 2014) 10
Figure 12: Selective Heat Sintering (THRE3D, 2014) 11
Figure 13: Selective Laser Melting (THRE3D, 2014) 11
Figure 14: Selective Laser Sintering (THRE3D, 2014) 12
Figure 15: Laminated Object Manufacturing (THRE3D, 2014) 12
Figure 16: Ultrasonic Additive Manufacturing (THRE3D, 2014) 13
Figure 17: Digital Light Processing (THRE3D, 2014) 13
Figure 18: Stereolithography (THRE3D, 2014) 14
Figure 19: Fused Deposition Modeling (THRE3D, 2014) 14
Figure 20: 3D print house and house assembled (Blain, 2014) 16
Figure 21: Applications in an automobile (Giffi et al., 2014) 17
Figure 22: Urbee the first 3D printed car (Giffi et al., 2014) 18
Figure 23: Strati 3D printed car (Ulanoff, 2014) 18
Figure 24: SuperDraco Engine Chamber (Norris, 2014) 19
Figure 25: Conventional production of aid shells (Snyder et al., 2014). 20
Figure 26: Custom made aid shells with 3D print (Snyder et al., 2014) 20
Figure 27: 3D printed key (Ulanoff, 2014) 22
Figure 28: Breakeven between Additive and Conventional manufacturing (Cotteleer and Joyce, 2014) 23
Figure 29: Complex 3D printed model (Cotteleer and Joyce, 2014) 24
Figure 30: Cartesian Printer, and Cartasian Graph (PrintSpace, 2014). 25
Figure 31: Delta Printer (PrintSpace, 2014) 26
Figure 32: Scara Printer (PrintSpace, 2014) 26
Figure 33: Polar Printer (PrintSpace, 2014) 27
Figure 34: Printers main components (THRE3D, 2014) 27
Figure 35: FDM 3D printing filament.(Smith, 2014) 28
Figure 36: HIPS dissolving in Limonene (Smith, 2014) 30
Figure 37: Object printed in wood like material 31
Figure 38: Object printed in Carbon PLA (Smith, 2014) 32

Figure 39: Objects in ceramic filament (Smith, 2014) 32
Figure 40: Chocolate 3D printer 35
Figure 41: Spring shock absorber 36
Figure 42: Up Plus 2 3D printer 37
Figure 43: 45 degree rule (Kaziunas, 2013). 40
Figure 44: Sliced and assemble for best orientation (Kaziunas, 2013) 41
Figure 45: Assembly sketch 42
Figure 46: Exploded view of shock absorber system 43
Figure 47: Sketch of spring 45
Figure 48: Type of threads on bolts and nuts 46
Figure 49: Sketch of cylinder 47
Figure 50: Sketch of Piston with rod 47
Figure 51: Seal (left) and bump stopper (right) 48
Figure 52: Preload adjuster (left) and locking ring (right) 48
Figure 53: Bottom end cap 49
Figure 54: Top end cap 49
Figure 55: Eccentric cam with a flat-faced follower 50
Figure 56: Eccentric cam with shaft 50
Figure 57: Bottom cap with flat-faced follower 51
Figure 58: Upper stand support 51
Figure 59: Cam stand support 51
Figure 60: Type of fills 53
Figure 61: 3D printed shock absorber in ABS 54
Figure 62: 3D printed cap with sanded surface (left,) and upside down printed cap (right) 55
Figure 63: Horizontal 3D print spring 56
Figure 64: Shifted 3D print spring 57
Figure 65: Temperature tests on TPE printing 59
Figure 66: BuildTak sheet install on perboard. 60
Figure 67: Successful bump stopper printed on TPE 61
Figure 68: Single printed shock absorber 62
Figure 69: Single print shock absorber with support material 63
Figure 70: Interior fill of springs. 64
Figure 71: Spring rate measurement. 65
Figure 72: Acetone vapor bath 69
Figure 73: Spring after surface treatment 70
Figure 74: SEM image of 3D printed fracture surface with no acetone vapor treatment (Chapman et al., 2014). 71
Figure 75: SEM image of 3D print fracture surface after acetone vapor treatment (Chapman et al., 2014) 71
Figure 76: Assembled shock absorber 72
Figure 77: Functional shock absorber 72

List of Tables

Table 1: 3D printing applications (Cotteleer et al., 2013) 15
Table 2: UpPlus2 specifications 39
Table 3: Components for the system 43
Table 4: Spring specifications 45
Table 5: Stiffness of the springs 66
Table 6: Price of ABS and TPE 67
Table 7: Cost, time and setting of each component 67

Abstract

Since 2010, 3D printer technology has shown explosive growth thank to the open source and DIY communities. The Fused Deposition Manufacturing Technology is the most available and has become significantly less expensive. 3D printers are more accessible now a days, where at a hobbyist level they are available for as little as 500 USD. The main disadvantages of this technology are the materials available and the printers' resolution, although extensive research and experiments are being carried out all around the world to improve every aspect.

Because this technology is growing so fast it has evolved from Rapid Prototyping used for building physical model of prototypes, to Rapid Tooling allowing to build tools and molds, and finally to Rapid Manufacturing that can build end user parts. Soon everyone will be able to create custom parts with localized manufacturing. However, Rapid Manufacturing is still on a developing stage where more research and investigation is needed. With a functional shock absorber, which was designed for the Up Plus 2 desktop 3D printer, this project explores the benefits, the material involved and post-process of Fused Deposition Manufacturing. The study shows significate information and data about 3D printing with current applications and research.

As a result for this project it was concluded that ABS can work as a functional spring, but there still many challenges for printing complex objects in a desktop 3D printing. The final product was tested and showed promising results with advantages and disadvantages that are discussed and analyzed. A guide for printing on ABS and the new experimental material TPE is provided for anyone interested in this field. Finally, significant information about the surface treatment to improve the properties of the printed model is explained and carried out to improve the spring properties.

1. Chapter 1 Introduction

Humanity used to dream only through science fiction novels about the technology and advances that today we have achieved. Now a days we are surrounded by a variety of hi-tech deceives, from "smartphones to wearable technologies, such as fitness trackers, glasses, sleeping monitors, watches and others that are quickly showing themselves to be the latest development of mobility and location marketing" (Fishman, 2014). However, in order to create new advanced devices the manufacturing process has to develop as well. In the manufacturing area a new technology has proven to be very promising and is called rapid prototyping or 3D printing. A desktop printer prints ink into a paper in 2D, whereas a 3D printer prints three dimensional objects that can be manipulated and hold. This technology is worldly renowned and it's said that it will revolutionize the way we live. Lipson and Kurman (2013) believe that "in a 3d printing world, people will make what they need, when and where they need it". This promising worldview and beneficial lifestyle has launched the investigation and aspiration to develop to its fullest potential the 3D printer.

The 3D printing is an additive manufacturing technology also known as rapid prototyping. It is an advanced technique to rapidly produce a three-dimensional model of a physical part or assembly using computer-aided design. Nowadays there are different types of rapid prototyping technologies but this study will mainly focus in fused deposition modeling, also known as FDM. 3D printers where once seen as exclusive for high tech businesses but are now moving from the factory to the desktop. The fast growth of this technology has allowed great inventions and a price drop, therefore making 3D printings accessible to the average consumer.

At the beginning 3D printing was mostly seen as a tool to shape and bring to life artistic designs, but in the last few years this technology is evolving to a point where mechanical devices and useful parts can be printed. However, one of the limitations as Slavkovsky (2012) states is that "working on 3D printing is often limited by materials or standard designs". The materials that are used depend mostly on their heat resistance properties; nevertheless new materials are being developed at the same time this technology grows, opening doors to new creations. Furthermore, the easy access to computers and Internet, combined with the online tutorials and new CAD software allow people to design, develop and manufacture in a way that was never thought possible. The access to information has great impact in society as said by Isakow (2014)

“troughout history, the art and scrience of printing has changed dramatically and each major innovation was followed by a significant change in society. The reason for this has more to do with access to information”.

As this technology rapidly changes more practical and useful devices will be manufactured this way. The technology is now used in a great variety of industrial sectors with positive benefits, as stated by Stratasys (2014) the “rapid prototyping allows companies to turn innovative ideas into successful end products rapidly and efficiently.” This manufacturing process is much simpler and cheaper compared to the existing ones, and it still has much to grow.

Given the importance and impact that this new technology has created, the main objective of this investigation is to explore the world of 3D printing, the printing materials and also to understand how useful it is and will be. A practical mechanical spring shock absorber will be designed and build using a commercial in-house 3D printer. Herewith, explore the potentials of this technology, also the materials and post-processes that are involved. It’s expected to reveal significant facts about how 3D printing works and benefit as a guide for others interest in this field. Exploring and growing this area of rapid manufacturing can bring great benefits to society and improve the quality of our lives, but it needs further experimenting and researching to keep advancing. Being able to print anything from food to plastic or metal is a science fiction dream that will certainly be achieved any time soon.

1.1. History of 3D printing

The 3D printing method, which allows to building three-dimensional objects, has been around since the 1980s; however it wasn’t until around 2010 that this technology became more affordable and practical.

In order to develop this technology it was first necessary the creation and improvement of computers and software. The computer aided design (CAD) is defined as the use of computers to assist in the making, optimization, analysis and modification of 2D or 3D designs (Narayan, 2008). The CAD software started being developed in the 1960s but it was not until 1980s when this software was able to handle a full solid model design (Cadazz, 2004). With this software and faster computers the rapid prototyping started to emerge.

The greatest step toward development started in 1984 when Charles Hull invented an additive manufacturing process that he called stereolithography, this technology allowed for the first time the creation of a 3D object from digital data (Krant, 2014). This technology works by curing a liquid material and the process consisted on a vat of liquid ultraviolet curable photopolymer and an ultraviolet laser that solidifies the liquid layer by layer until it creates a solid (Thre, 2014). Figure 1 shows how this technology works and this was a complex and expensive process. After a couple of years in 1986 Hull founded the 3D Systems Inc. to simplify, improve and commercialize this process. Later on in 1992 the company builds the first stereo lithographic machine or SLA printer that had a more advanced viscosity liquid allowing to reduce the time of building the object (Zent, 2013).

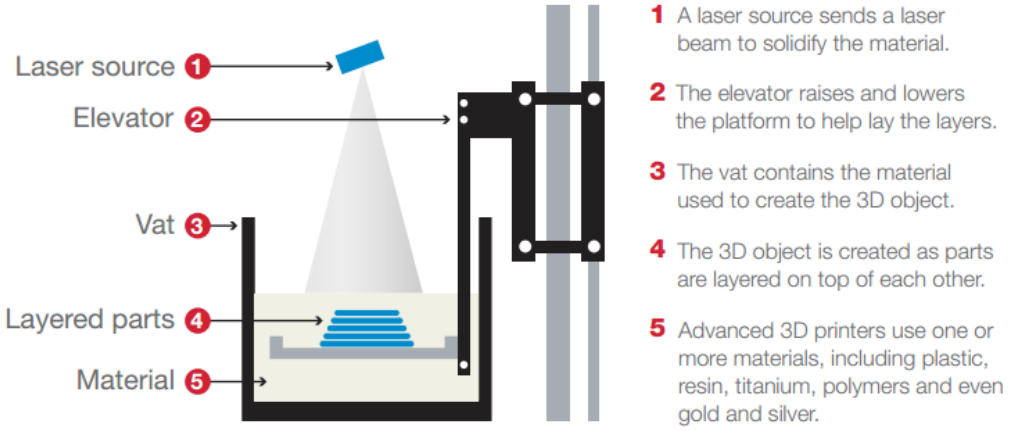
Laser source 1
Elevator 2
Vat 3
Layered parts 4
Material 5
1 A laser source sends a laser beam to solidify the material.
2 The elevator raises and lowers the platform to help lay the layers.
3 The vat contains the material used to create the 3D object.
4 The 3D object is created as parts are layered on top of each other.
5 Advanced 3D printers use one or more materials, including plastic, resin, titanium, polymers and even gold and silver.

Figure 1: Stereo Lithography Technology (Zent, 2013)

On the other hand, in the late 1980s Scott Crump develops a different type of additive technology called fused deposited modeling or FDM where instead of curing a liquid material it melts a solid material. The FDM works by melting a thin thermoplastic film and extruding it through a control nozzle into a platform were layer by layer the model is manufactured as shown in Figure 2 (Junction, 2013). It was not until 1992 when Stratasys Inc. introduced and commercialized the first 3D printing based on this technology that was much simpler and cheaper (Stratasys, 2014). These pioneers of additive technologies where the initiators of rapid prototyping, but as stated by Lipson and Kurman (2013) the "process was too complicated and slow, and its machines were too expensive for margin conscious manufacturing companies to embrace".

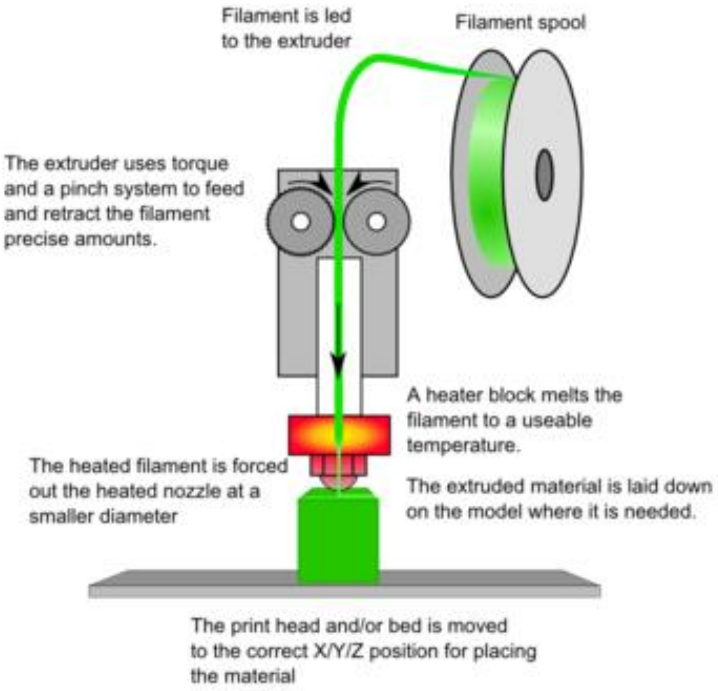
Filament is led
to the extruder
Filament spool
The extruder uses torque
and a pinch system to feed
and retract the filament
precise amounts.
A heater block melts the
filament to a useable
temperature.
The heated filament is forced
out the heated nozzle at a
smaller diameter
The extruded material is laid down
on the model where it is needed.
The print head and/or bed is moved
to the correct X/Y/Z position for placing
the material

Figure 2: Fuse Deposition Modeling Technology (Junction, 2013)

The major growth of rapid prototyping started from the 2000s due to the expiration of the patents and the easy access to new information. In 2004 Adrian Bowyer realized that 3D printing could be so useful that it could even manufacture a significant part of itself making it a self replicator (Bradshaw et al., 2010). This idea of self-replicating didn't interest any seller due to the reason that it was not marketing profitable. Therefore, he made this machine and gave away all the designs through the web in the General Public License (GNU) for free (Bradshaw et al., 2010). This was the beginning of the RepRap project or replicating rapid-prototyper that seeks to make 3D printing with FDM technology accessible to everybody, by means of the open source and do it your self-method (DIY). Figure 3 shows the first RepRap project printer which was released in 2007 and named "Darwin". After the success of the Darwin project in 2007 the second version was introduced as "Mendel" and then followed by "Prusa Mendel" and "Huxley". They are named after famous evolutionary biologist in order to symbolize the RepRap idea ('RepRap' n.d.).

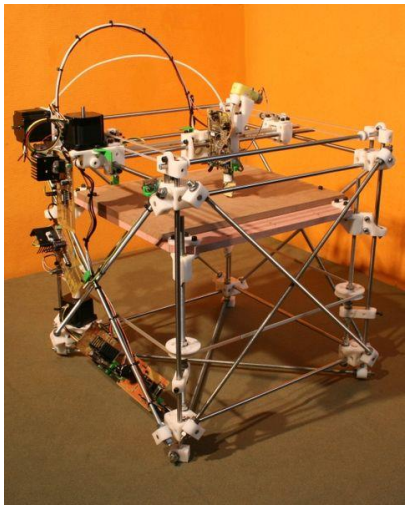

Figure 3: The RepRap first version "Darwin" ('RepRap' n.d)

The RepRap project opened many doors for common people to start building, modifying and improving 3D printers. The printing quality was not as great as the commercial ones, but the cost was much less. At this time the SD-300 developed by Solido Ltd was the cheapest 3D printer pricing around 16000 USD, and others went up to 400000 USD (Bradshaw et al., 2010). Whereas, the price of all the materials for the RepRap printer was around 600 USD which made it affordable for any individual and could be used in industries or homes (Bradshaw et al., 2010). However, there was a limitation because the user had to possess good technical expertise in order to understand and build the printer. In 2009 some garage star-ups like Bits from Bytes and MakerBot, took advantage of this problem and came up with affordable 3D printers sold as prefabricated kits that only required the final assembly from the customer (Ratto and Ree, 2012). These where still open source and based on RepRap technology but they were DIY lite making it even more affordable for people that didn't had too much expertise in this field.

The price has continued to drop down on 3D printers thanks to the rapid development of open source and DIY method. There are public domains on the web like Thinkgivers and Cubify that allowed anyone to share and download any design for free. Since 2010 3D printers have gone from a general ranging price of from 20000 USD to less than 1000 USD (Krant, 2014). Nowadays even companies like Stratasys which makes ready to use close-source printers, that are just plugged and used, for around 2500 USD (Ratto and Ree, 2012). This technology is developing to be more user friendly and with accessible prices. Even though it works just in plastics, which is a limitation, there is a lot of active research going on in order to extend the

range of materials (Bradshaw et al., 2010). Currently there is a big open source community and it is being applied in many fields like aerospace, military, architecture, construction, engineering, medical, fashion, automotive and industrial design and more. As the additive manufacturing technology advances more practical uses will show up. In addition, now a days there are 3D digitizers, 3D sensors and 3D scanners that complement and make this technology more powerful (Krant, 2014).

1.1. 3D Printing Processes and Technologies

The process of joining material to obtain an object, also known as additive manufacturing, has continuously developed since it was invented. It creates objects through a sequential layering process which allows complex and intricate designs. As shown in Figure 4 there are five sequential processes in order to create the desire object. First, a CAD based model is created and then converted to a Stereolithographic file (.STL) that breaks down the surface into logical series of facets. A facet is a triangle which represents a part of the surface of a 3D model that is then used for the slicing algorithm (Burns, 1999). The STL file is then slice into thin cross-sectional layers that allowed the model to be 3D printed. Since some models require support material the last processes is removing it and cleaning it, or any other finishing the model may require.

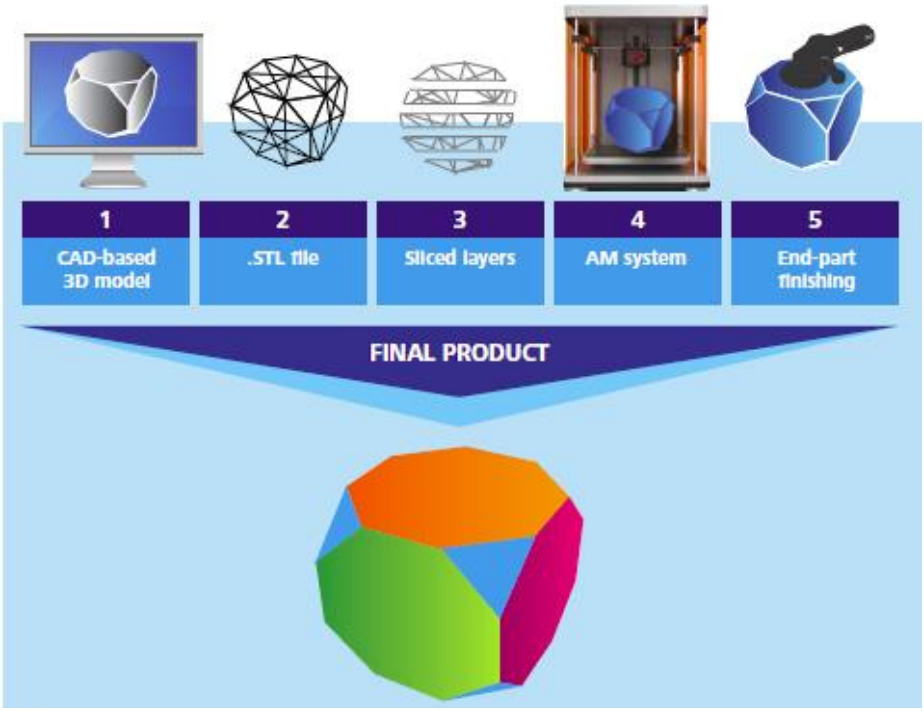

Figure 4: 3D print process flow (Cotteleer et al., 2013)

Currently there are various additive processes available and each one uses different technologies. Each technology is distinguished by the material it uses and by the technique of consolidation. There are 7 processes and each one has its own modifications, a brief explanation of all these 3D printing processes is shown below.

1.1.1. Binder Jetting

- Binder Jetting also known as Inkjet Powder Printing (PP). It is a great choice for 3D printing in full color and the final product has less visible layer definitions. As shown in Figure 5 it prints with a head that moves across a bed of powder and sprays a liquid binding material. Then a thin layer of powder is deposited by an automated roller across the completed section in order to form the next layer, and this process is repeated to build the object one layer at a time (THRE3D, 2014). This process enables color prints with high speed but there is a limited range of materials (Cotteleer et al., 2013).

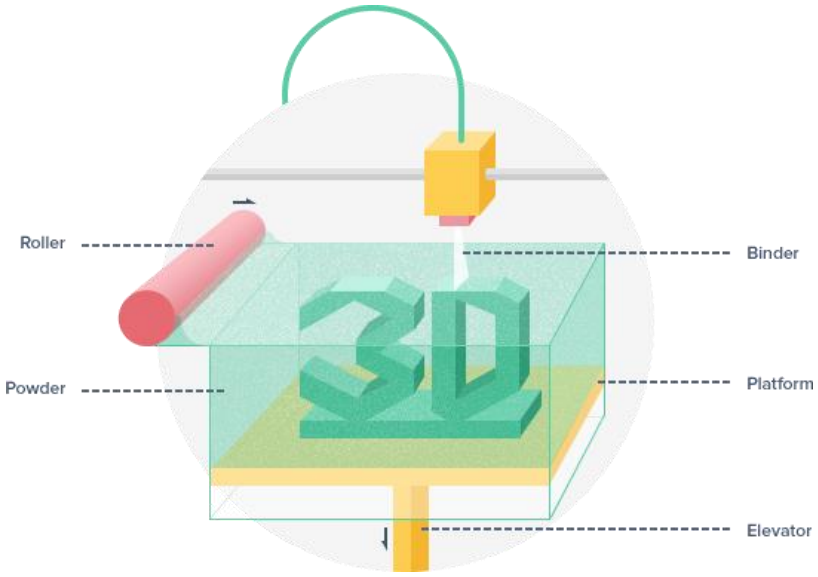

Figure 5: Binder Jetting (THRE3D, 2014)

1.1.2. Material Jetting

- This type of printer looks more like a traditional 2D printer compared to other 3D printers. As shown in Figure 6 it moves a print head around the printer area laying a photopolymer, which is a light reactive plastic and a UV light that passes over it solidifying it. This process is repeated until the object is formed and it has a high resolution that can go down to 16 microns of layer height(THRE3D, 2014).

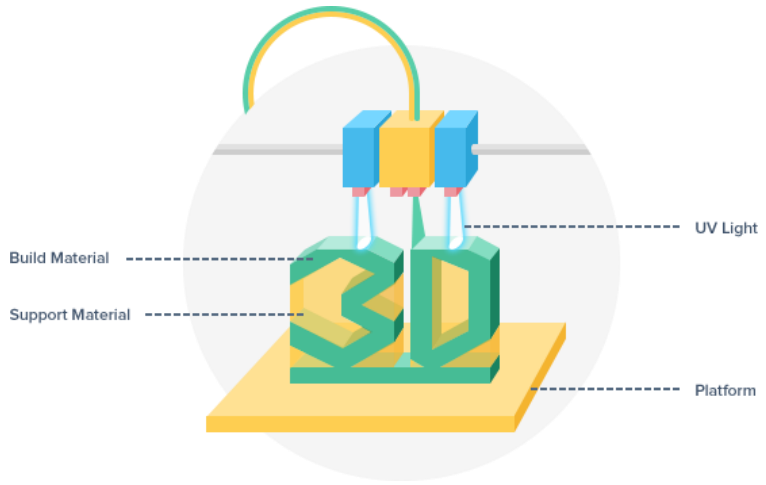

Figure 6: Material Jetting (THRE3D, 2014)

1.1.3. Direct Energy Deposition

- Electro Beam Direct Manufacturing (EBDM): It has one of the largest fabrication abilities and can print almost any metal alloy. This process is used exclusively by Sickay, Inc. and it melts metal wire to create an object inside a vacuum chamber. The wire is fed into a molten pool formed by an electron beam on a metallic substrate. The deposition solidifies immediately after the electron beam passes so as it moves it forms the object one layer at a time as shown in Figure 7 (THRE3D, 2014).

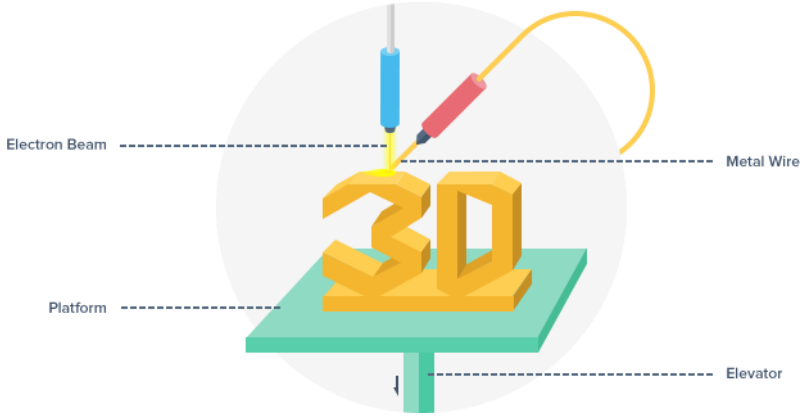

Figure 7: Electro Beam Direct Manufacturing (THRE3D, 2014)

- Ion Fusion Formation (IFF): It is used by Honeywell Aerospace. It liquefies metal wire or powder with a plasma welding torch. It adds layers of metal wire like the EBDM process but instead it uses a plasma of heated argon as the energy source that melts the material as seen in Figure 8. It uses materials that come either in a wire or powder form like tool steel alloys and nickel superalloys (THRE3D, 2014).

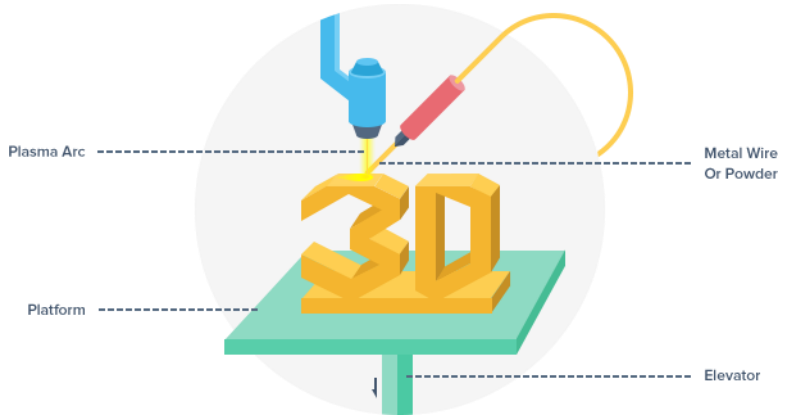

Figure 8: Ion Fusion Formation (THRE3D, 2014)

- Laser Powder Forming (LPF): It can fabricate large objects and also repair or add volume to an existing metal part. As shown in Figure 9 a laser head controlled by a multi axis joint is used to melt the surface area and a stream of powdered metal, which is then delivered onto the target forming a melt pool. The computer controlled deposition tool adds the layers where it's needed, building the object layer by layer (THRE3D, 2014).

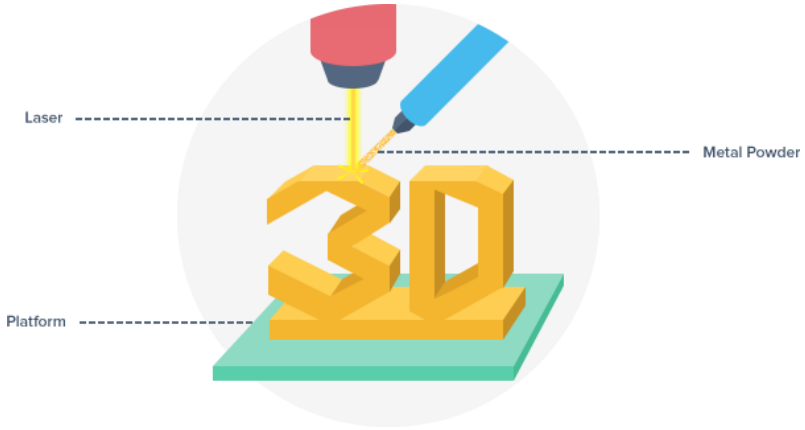

Figure 9: Laser Powder Forming (THRE3D, 2014)

1.1.4. Powder Bed Fusion

- Direct Metal Laser Sintering (DMLS): It fabricates an object by melting and fusing metal powder using a focused laser beam in a chamber of inert gas as shown in Figure 10. An automated roller adds a new layer of material when the last one is cured and the process is repeated to build the object. It works with multi-component alloys, theoretically it can use almost any metal alloy. Now existing alloy with stainless steel, maraging steel, cobalt chrome, Inconel, aluminum and titanium (THRE3D, 2014). It is not suitable for large parts but it allows to print complex geometries (Cotteleer et al., 2013).

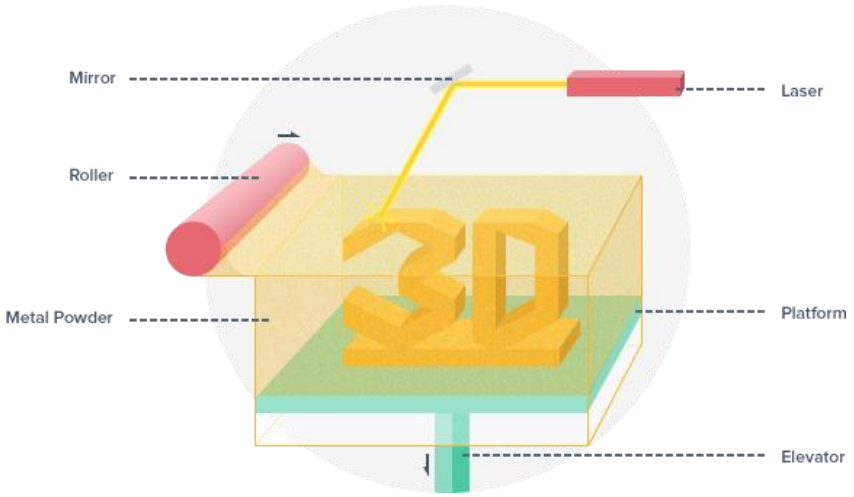

Figure 10: Direct Metal Laser Sintering (THRE3D, 2014)

- Electron Beam Melting (EBM): As shown in Figure 11 it uses an electron beam that melts metal powder inside a vacuum. When a layer is finished the bed moves down and a roller puts a new layer of material in order to build the object one layer at a time. The materials that are suitable include different types of titanium and cobalt chrome (THRE3D, 2014).

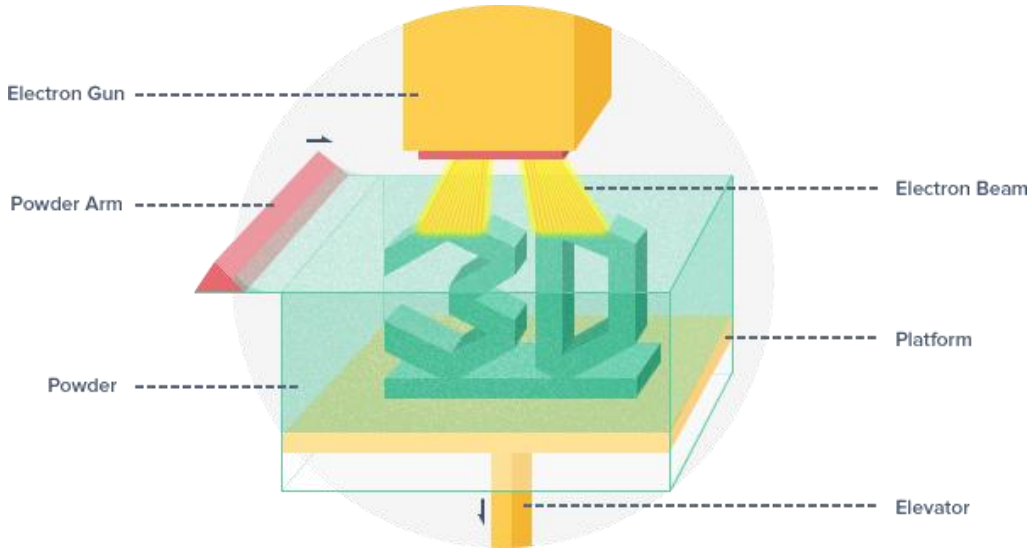

Figure 11: Electron Beam Melting (THRE3D, 2014)

- Selective Heat Sintering (SHS): As shown in Figure 12 it applies heat to layers of thermoplastic powdered using a thermal print head which cures the powder. Next, a roller adds a new layer of material which is then cured, and by repeating this process the object is created. It is important to note that it's cheaper than SHS because it doesn't use a laser

(THRE3D, 2014). It is a relatively new technology which doesn't need a support structure.

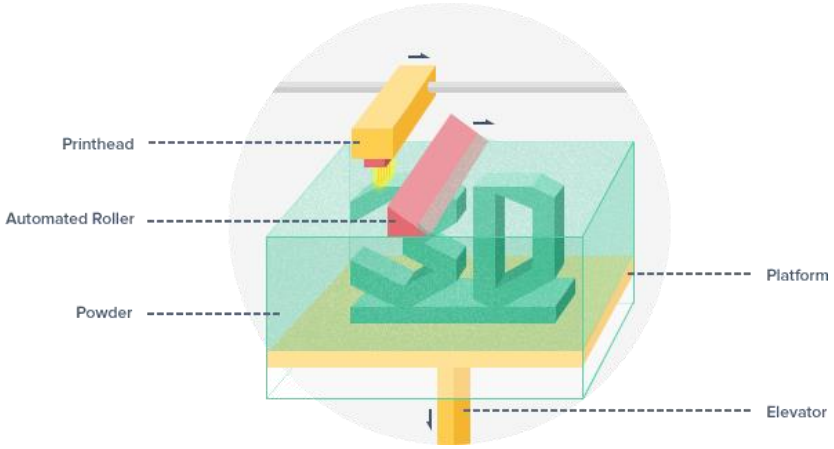

Figure 12: Selective Heat Sintering (THRE3D, 2014)

- Selective Laser Melting (SLM): As shown in Figure 13 this process melts a metal powder forming a melt pool in a chamber of inert gas by using a laser and then a roller adds a new layer of material that can be melted again on top of the last cured layer. It works with metals including titanium, cobalt chrome, stainless steel, aluminum and tool steel (THRE3D, 2014). It has high printing speed and it doesn't require support structure. However, final products have a rough finish surface and the accuracy is limited to the powder particle size (Cotteleer et al., 2013).

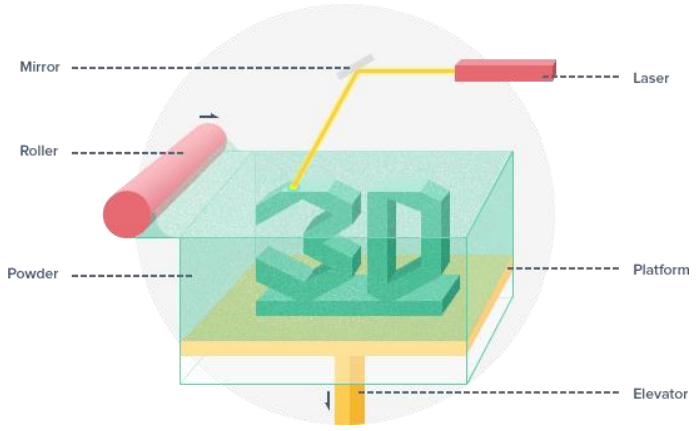

Figure 13: Selective Laser Melting (THRE3D, 2014)

- Selective Laser Sintering (SLS): As shown in Figure 14 this process is similar to the SLM where a laser sinters a powdered material and a roller adds new layer of material to form the part. The difference is that material is heated below the melting point until the

particles fuse with each other. It also uses a wider range of materials such as thermoplastics, metal powders, and ceramic powders (THRE3D, 2014).

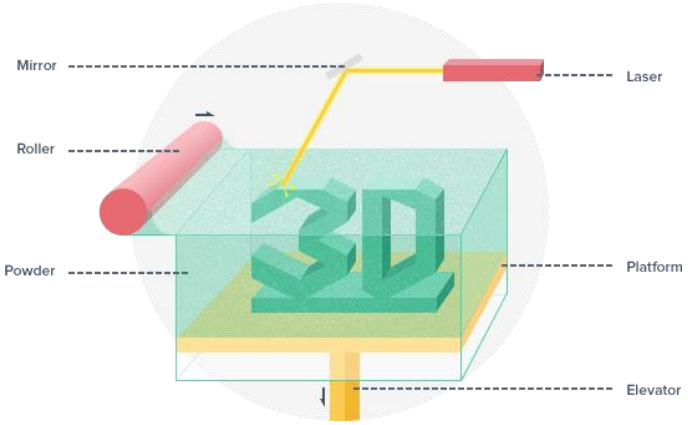

Figure 14: Selective Laser Sintering (THRE3D, 2014)

1.1.5. Sheet Lamination

- Laminated Object Manufacturing (LOM): As shown in Figure 15 this process works by adding layers of adhesive coated paper, plastic or metal which are non-toxic. Each layer or sheet of thin material are cut to shape with a laser cutter and then successively glued together. This is repeated until the object is created, after this process it usually needs additional adjustments by machining or drilling the part (THRE3D, 2014).

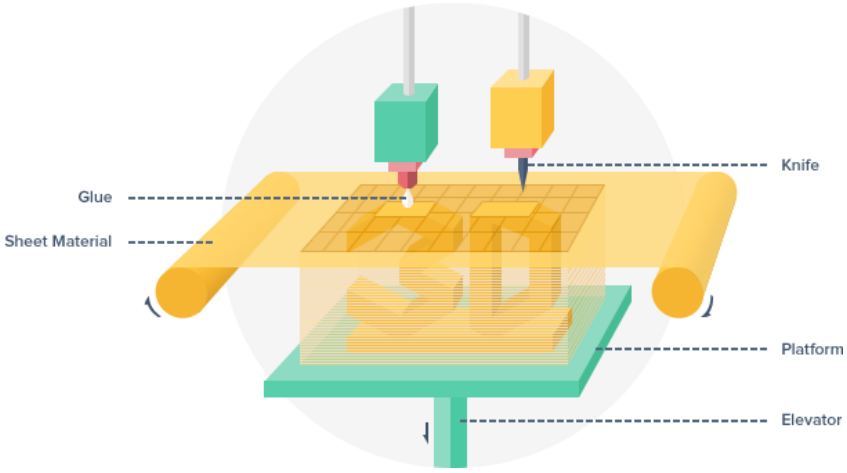

Figure 15: Laminated Object Manufacturing (THRE3D, 2014)

- Ultrasonic Additive Manufacturing (UAM): It uses the sheet lamination process where thin sheets of metal are joined together until the object is build. An ultrasonic welding is used to bond the sheets and then a CNC mill cuts the excess material. This is repeated until the object is form layer by layer, as shown in Figure 16. It can create parts with

multiple combinations of metals for special applications. It can work on metallic materials like titanium, copper, molybdenum, tantalum, stainless steel, nickel, silver, and aluminum (THRE3D, 2014). The accuracy is relatively less compared to others but can build big parts in shorter time (Cotteleer et al., 2013).

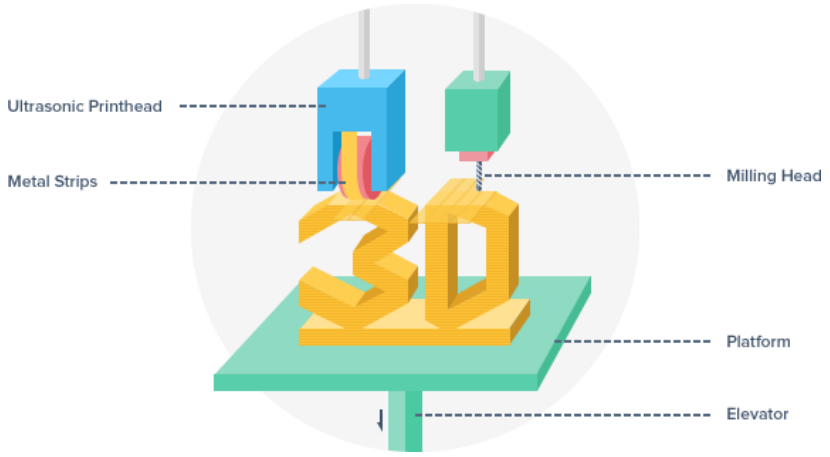

Figure 16: Ultrasonic Additive Manufacturing (THRE3D, 2014)

1.1.6. Light Photopolymerization

- Digital Light Processing (DLP): As shown in Figure 17 an image of the object is projected in layers into a vat of photopolymer that reacts to the projecting light in order to cure and harden the desired part. This is repeated by lowering the platform and projecting the new layer until the object is completed (THRE3D, 2014). It has a high precision which allows complex shapes but the weaknesses are the limited variety of materials (Cotteleer et al., 2013).

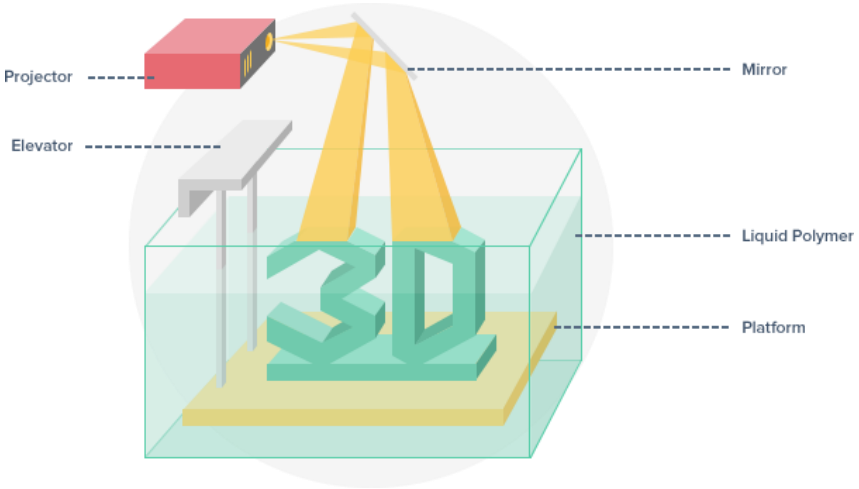

Figure 17: Digital Light Processing (THRE3D, 2014)

- Stereolithography (SLA): As shown in Figure 18 a liquid photopolymer resin is cured using a beam of UV light sent from a laser which causes the resin in contact to react and solidify. As the computer controlled laser moves it cures the resin one layer at a time forming the object (THRE3D, 2014). The advantages are it allows complex geometries with high detail definition. Disadvantages are that requires support structure and post-curing (Cotteleer et al., 2013).

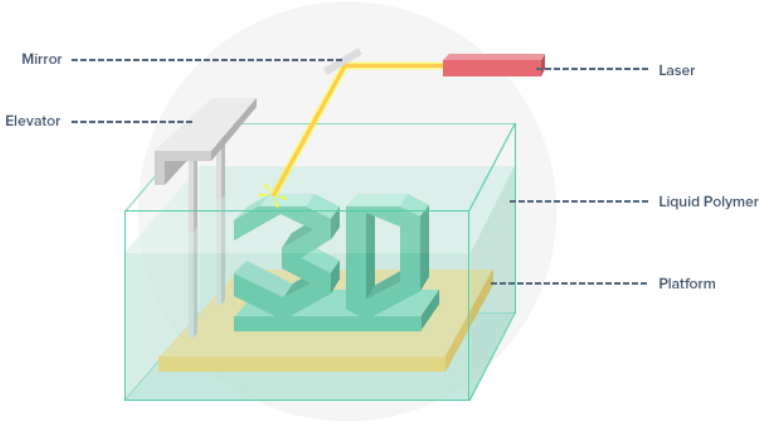

Figure 18: Stereolithography (THRE3D, 2014)

1.1.7. Extrusion

- Fused Deposition Modeling (FDM): This simple process is cheap and it is also known as Fused Filament Fabrication (FFF) in the open source community. As shown in Figure 19 it works with a heated nozzle that extrudes the material and moves following a path. The melted material forms the layers that are instantly harden so the next layer can bond on top, this process is repeated until the object is finished (THRE3D, 2014). It can print complex geometries but it has a low surface finishing and it takes longer time compare to SLA (Cotteleer et al., 2013).

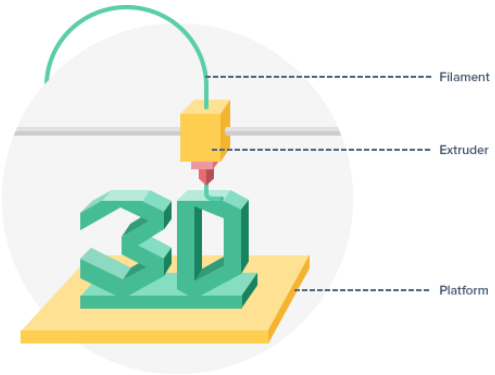

Figure 19: Fused Deposition Modeling (THRE3D, 2014)

1.2. Uses and Applications

3D printers are currently being used all around the world in many different areas and with diverse purposes. It started with rapid prototyping purposes and now it's being used from hobbyist to organizations and even end products. Having materials ranging from food to concrete and cells, it's being applied in a variety of fields as a competitive advantage. With the improvements on accuracy, materials and printing sizes many industries are using it today, including healthcare, automotive, aerospace and defense, fashion design, jewelry and art, architecture and interior design and others (Jewell, 2013). In Table 1 there is a brief description of current applications on some of the industries named above and the potential future applications using 3D printing.

Table 1: 3D printing applications (Cotteleer et al., 2013)

INDUSTRIES	CURRENT APPLICATIONS	POTENTIAL FUTURE APPLICATIONS
COMMERCIAL AEROSPACE AND DEFENSE[17]	• Concept modeling and prototyping • Structural and non-structural production parts • Low-volume replacement parts	• Embedding additively manufactured electronics directly on parts • Complex engine parts • Aircraft wing components • Other structural aircraft components
SPACE	• Specialized parts for space exploration • Structures using light-weight, high-strength materials	• On-demand parts/spares in space • Large structures directly created in space, thus circumventing launch vehicle size limitations
AUTOMOTIVE[18]	• Rapid prototyping and manufacturing of end-use auto parts • Parts and assemblies for antique cars and racecars • Quick production of parts or entire	• Sophisticated auto components • Auto components designed through crowdsourcing
HEALTH CARE[19]	• Prostheses and implants • Medical instruments and models • Hearing aids and dental implants	• Developing organs for transplants • Large-scale pharmaceutical production • Developing human tissues for regenerative therapies
CONSUMER PRODUCTS/RETAIL	• Rapid prototyping • Creating and testing design iterations • Customized jewelry and watches • Limited product customization	• Co-designing and creating with customers • Customized living spaces • Growing mass customization of consumer products

1.3. Examples

In the architecture and construction industry uses range from printing scale model to real houses. A Chinese company called WinSun, has 3D printed 10 small houses in 24 hours using recycled materials. The material consists of a mixture of glass fiber and scrap concrete which is layer up in a structural pattern with a 6.6m tall, 10m wide and 32m long 3D printer. The houses costs as little as 4800 USD and each one is approximately 2,100 square feet. They are printed at a central factory by blocks and then assembled on site as shown in Figure 4. The diagonal reinforced pattern minimizes the amount of material used and acts as insulation, also it has calculated gaps for later insertion of plumbing and electrical components (Blain, 2014).

Figure 20: 3D print house and house assembled (Blain, 2014)

At the moment the automotive industry is printing dashboards and cooling vents in some vehicles. Figure 21 shows some current applications of 3D printing in the automobile industries and future applications.

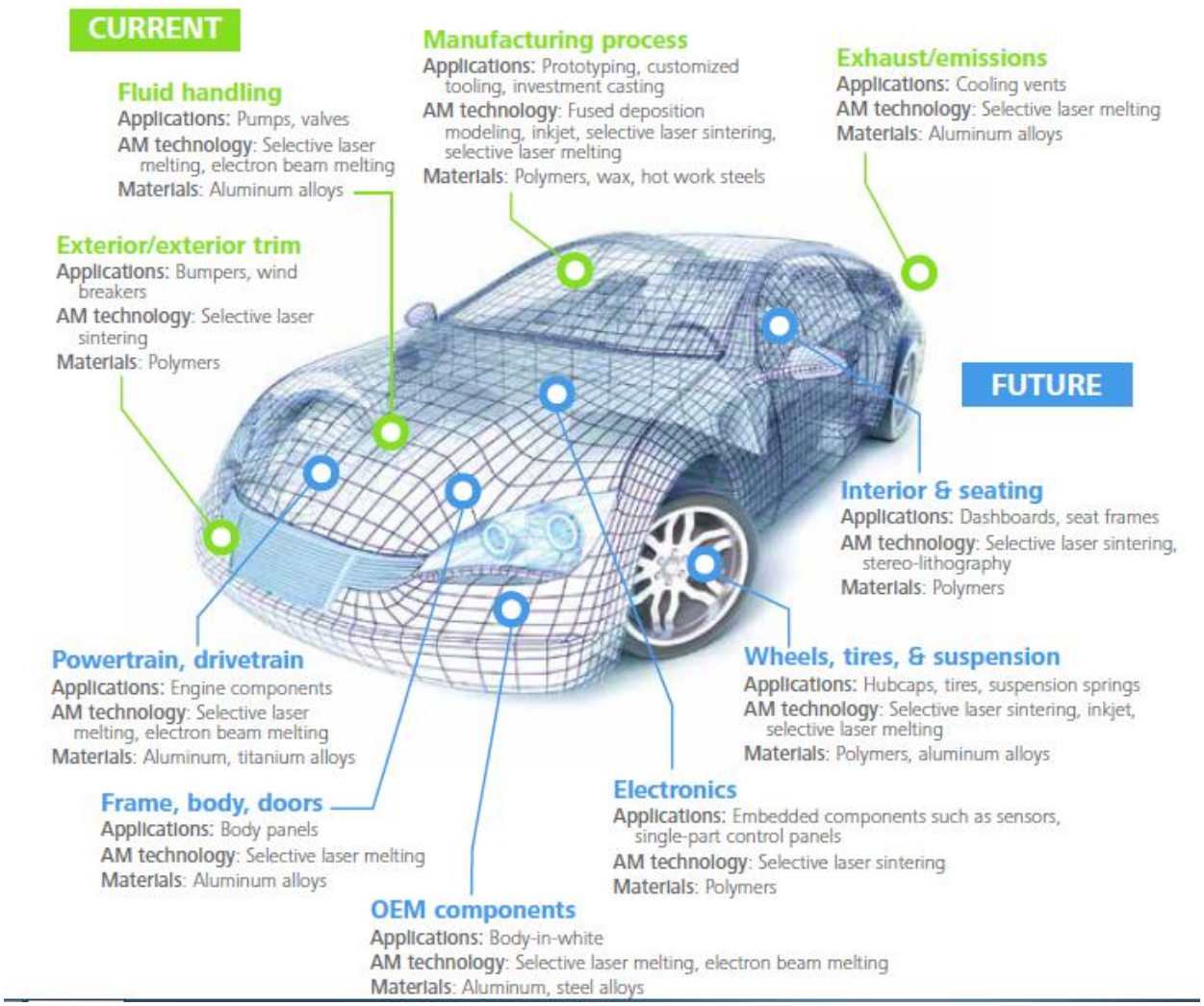
CURRENT
Fluid handling
Applications: Pumps, valves
AM technology: Selective laser melting, electron beam melting
Materials: Aluminum alloys
Manufacturing process
Applications: Prototyping, customized tooling, investment casting
AM technology: Fused deposition modeling, inkjet, selective laser sintering, selective laser melting
Materials: Polymers, wax, hot work steels
Exhaust/emissions
Applications: Cooling vents
AM technology: Selective laser melting
Materials: Aluminum alloys
Exterior/exterior trim
Applications: Bumpers, wind breakers
AM technology: Selective laser sintering
Materials: Polymers
FUTURE
Interior & seating
Applications: Dashboards, seat frames
AM technology: Selective laser sintering, stereo-lithography
Materials: Polymers
Powertrain, drivetrain
Applications: Engine components
AM technology: Selective laser melting, electron beam melting
Materials: Aluminum, titanium alloys
Wheels, tires, & suspension
Applications: Hubcaps, tires, suspension springs
AM technology: Selective laser sintering, inkjet, selective laser melting
Materials: Polymers, aluminum alloys
Frame, body, doors
Applications: Body panels
AM technology: Selective laser melting
Materials: Aluminum alloys
Electronics
Applications: Embedded components such as sensors, single-part control panels
AM technology: Selective laser sintering
Materials: Polymers
OEM components
Applications: Body-in-white
AM technology: Selective laser melting, electron beam melting
Materials: Aluminum, steel alloys

Figure 21: Applications in an automobile (Giffi et al., 2014)

A Swedish automaker called Koenigsegg has built a hyper car call the "One:1" that has 3D printed components like the side air ducts, side mirror internals, titanium exhaust components, and turbocharger assembles. With this they have been able to reduce the car weight and achieve a 1:1 power to weight ratio. Additionally, the exhaust tip is the biggest piece of titanium ever 3D printed (Davies, 2014).

In 2011 the company Kor built the first car using primary the additive manufacture technique. The name of the car is Urbee and they expect to release the Urbee 2 in 2015 which will have around 50 major body and interior parts 3D printed.

2011
URBEE
2015
Proposed
URBEE2
• Built external frame comprised of 20 separate panels built through rapid prototyping using fused deposition modeling (FDM)
• Partnered with a major rapid prototyping service bureau in production of the frame
• Used design and simulation software
• CAD modeling begun in 2013
• 3D print interiors in addition to the external body
• More parts—40–50 major body and interior parts will be 3D printed
• Greater complexity of parts which cannot be produced through traditional manufacturing methods

Figure 22: Urbee the first 3D printed car (Giffi et al., 2014)

The second 3D printed car, Strati, has just been released by the Local Motor. Strati, shown in Figure 23 was exhibit and first drive on September 13, 2014 at the Chicago Manufacturing Technology Show. The vehicle was printed in one piece using direct digital manufacturing, which is the first time this method has been used for a car. The total time to print was 44 hours which is a great improvement compare to the Urbee which took 2500 hours. This is the first 3D printed electric car that was build, assemble and then drive within 6 days. The large size BAAM machine developed by Cincinnati Incorporated was used for the production which deposits 40 pounds per hour of carbon reinforces ABS plastic (Ulanoff, 2014).

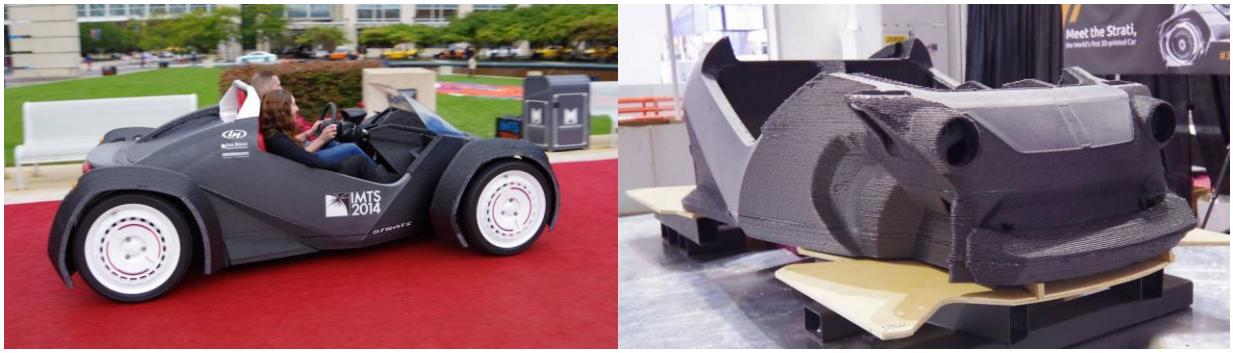

Figure 23: Strati 3D printed car (Ulanoff, 2014)

In the aerospace field this technology offers improvements that with traditional manufacturing methods couldn't be done. SpaceX launched the first successful rocket Falcon 9 rocket on January 6, 2014 with a 3D printed Main Oxidizer Valve in one of the engines. With typical casting method this could have taken months to produce, instead using 3D printing it took less than two days. But that's not all, using the direct metal laser sintering process this company has printed a SuperDraco Engine Chamber made of Inconel (nickel and iron alloy). The device has complex cooling channels, throttling mechanism, and an injector head, which would be extremely complex to build without 3D printing. This chamber shown in Figure 24 will provide propulsion-landing thrust and launch escape system for the Dragon version 2. It will produce up to 120,000 pounds of axil thrust and operate at a chamber pressure of 1,000 psi with extreme temperatures. Until now the chamber has been fired 80 times and it has successfully pass all the tests. These devices will allow the space capsule to land with the accuracy of a helicopter and will allow rapidly reuse, which will drastically lower the cost of space travel. SpaceX expects to Dragon V2 to make its first orbital spaceflight in 2015 (Norris, 2014).

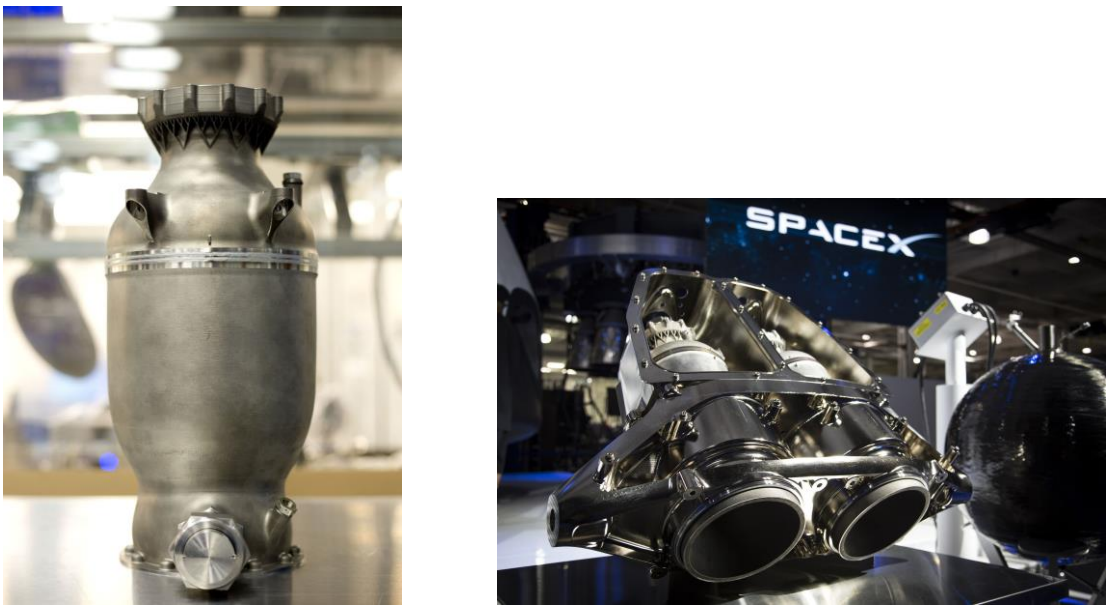

Figure 24: SuperDraco Engine Chamber (Norris, 2014)

Additionally jewelry and even guns can be made using 3D printing, however the medical field shows greater advances that can improve and save lives. It is helping people with new and cheaper prosthesis including arms and legs, and also successful implants. For example, in Newcastle an old women was implanted a 3D printed titanium pelvis. It was made out of

titanium powder and fused with a laser, which then was coated with a mineral that allowed new bone to grow. There has been an entire lower jaw implanted, a bionic ear, and even a tracheal splint to save the life of an infant with tracheobronchomalacia (Moore, 2014). Also the hearing aid and dental industries are making custom consumer devices that meet specific patient needs. These devices not only are custom made but also are much simpler to manufacture. The conventional manufacture a hearing shell device requires 10 steps as shown in *Figure 25*, whereas with 3D printing it takes only 4 steps as shown in Figure 26.

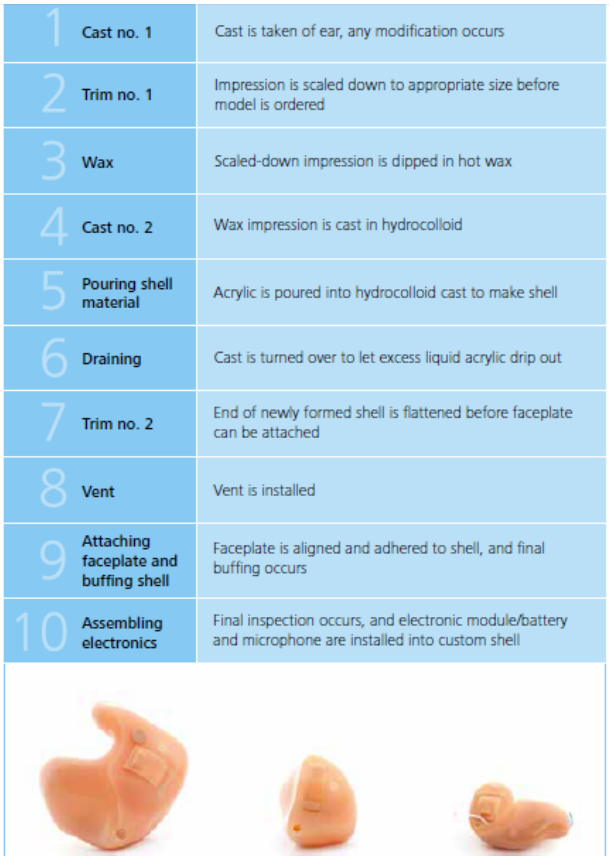
1 Cast no. 1
Cast is taken of ear, any modification occurs
2 Trim no. 1
Impression is scaled down to appropriate size before model is ordered
3 Wax
Scaled-down impression is dipped in hot wax
4 Cast no. 2
Wax impression is cast in hydrocolloid
5 Pouring shell material
Acrylic is poured into hydrocolloid cast to make shell
6 Draining
Cast is turned over to let excess liquid acrylic drip out
7 Trim no. 2
End of newly formed shell is flattened before faceplate can be attached
8 Vent
Vent is installed
9 Attaching faceplate and buffing shell
Faceplate is aligned and adhered to shell, and final buffing occurs
10 Assembling electronics
Final inspection occurs, and electronic module/battery and microphone are installed into custom shell

Figure 25: Conventional production of aid shells (Snyder et al., 2014).

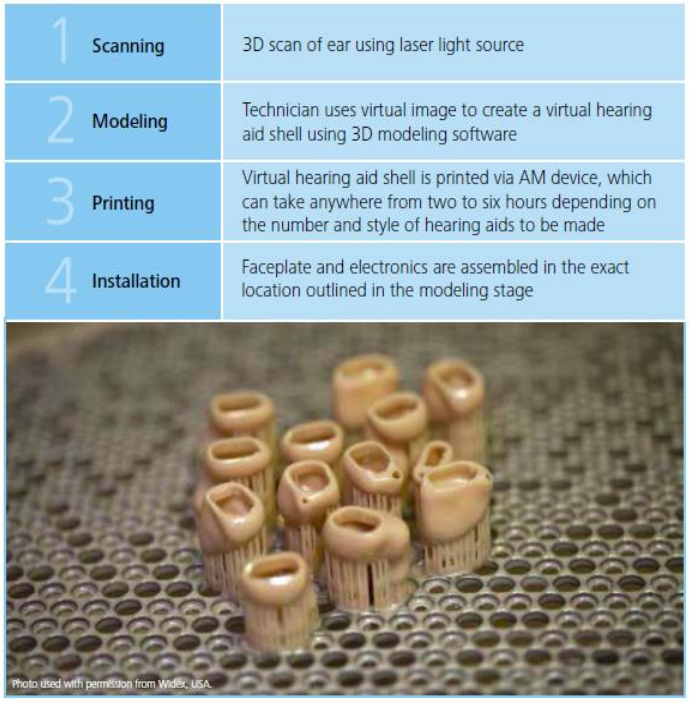
1 Scanning
3D scan of ear using laser light source
2 Modeling
Technician uses virtual image to create a virtual hearing aid shell using 3D modeling software
3 Printing
Virtual hearing aid shell is printed via AM device, which can take anywhere from two to six hours depending on the number and style of hearing aids to be made
4 Installation
Faceplate and electronics are assembled in the exact location outlined in the modeling stage
Photo used with permission from Widex, USA.

Figure 26: Custom made aid shells with 3D print (Snyder et al., 2014)

In 2009 Dr. Gabor Forgacs's from Organovo was able to print the first blood vessel using a 3D bio-printer (Krant, 2014). Since then, many biotechnology firms and universities have being studying this 3D bio-printing process. In this process layers of living cells are deposited onto a gel medium or sugar matrix in order to build body parts and vascular systems. For example, a US

team has created a template for blood vessels to grow into by using sugar, which they say is a step closer to create synthetic organs. They say synthetically engineered cells often die before the tissue is formed but with 3D printing using sugar to build material, one day it could work (Chen, 2012). Scientists from the Universities of Sydney, Harvard, Stanford and MIT have recently achieved a great accomplishment which brings us closer to bio-printing. They have bio-printed an artificial vascular network which imitates the body circular system. This is essential for the growing of large complex tissues as Dr Luiz Bertassoni (Sydney, 2014) says "one of the greatest challenges to the engineering of large tissues and organs is growing a network of blood vessels and capillaries".

The company Organovo released the first commercial bio-printer called the NovoGen which is used for studying the effects of new pharmaceuticals using functional 3D printed human tissue (Vesanto, 2012). Most recently a Singapore startup Bio3D Technologies has just announced a new 3D bio-printer called the Bio3D Life. This printer is able to print human tissues and cells for diagnostics and drug testing. It uses bio-materials like cells, proteins, bacteria, and bio-gel for 2D and 3D print with a precision of less than 10 microns, and just for 2400 USD (MaryAnn, 2014).

The USA Army has also many interest and projects working with 3D printing. They are currently experimenting to enhance uniforms and other gear. They believed 3D printing will allow them to make cloth or protective items that have stiff zones that move into soft areas where the body flexes (Pop, 2014). The Army is also working with Wake Forest University's Institute trying to achieve 3D printing skin and starting the clinical trials. This special 3D printer scans and measures the depth and size of the wound to print different cell types depending of the depths. Furthermore, it only needs a piece of skin $1/10^{th}$ the size of the wound to grow over the burn, thanks to the skin's natural healing abilities (MolitchHou, 2014). The main interests and research of the military is on printing warhead components, clothing, wearable sensors, food and bio printing.

Like all technologies it can be used for the wrong purposes as well. There are different cases with 3D printing. For example, a 34 year old man in southern France used a 3D printed fake cashpoint facades and stole thousands of euros from bank users (Helsel, 2014). Weyers and Holler's 3D print a "bump" key shown in Figure 27, only using a software they created called Photobump, a photo of the keyway and the manufacturer specific details about the lock series.

This 3D printed 'bumy' can easily open a wide range of locks. They stated they won't release the Photobumb to the public because thieves and spies could use it for breaking into facilities (Greenberg, 2014). There are also numerous 3D printed illegal guns showing that this technology can easily be used for negative applications.

Figure 27: 3D printed key (Ulanoff, 2014)

1.4. Potential Impact

Some years ago nobody would have thought modern manufacturing could be done without a factory. As 3D evolves it is believed that this technological advance will lead towards the third industrial revolution. The digitization of manufacturing will transform the way goods are made, impacting on society in every way (Anther, 2013). 3D printing has evolved from Rapid Prototyping (RP) used for building physical model of prototypes, to Rapid Tooling (RT) allowing to build tools and molds, and finally to Rapid Manufacturing (RM) that can build end user parts (Karlsen, 2013). The next step is improving printing resolutions and the materials that can be used. With this everyone will be able to create custom parts with localized manufacturing. As stated by Lipson and Kurman (2013, pg9) "Manufacturing and business as usual will be disrupted as regular people gain access to power tools of design and production."

3D printing is the only technology which builds by adding material instead of removing. This technology is mainly suited to low volume, small production runs, therefore offering companies a cost effective, more flexible and prompt alternative to traditional manufacturing methods (Cotteleer and Joyce, 2014). In Figure 28 a diagram shows the breakeven point between traditional production methods and the Additive manufacturing. The flat line illustrates that 3D

printing is efficient in low scale production where is not affected by the changes in volume. On the other hand, the traditional manufacturing method is efficient at high volumes but not at low ones. This study conducted by Deloitte University concluded that by using a variety of materials the Additive manufacturing could provide an efficient substitute for low and medium sized production runs. Also the reduction in material cost and equipment with better improvements will substantially increase the breakeven point (Cotteleer and Joyce, 2014).

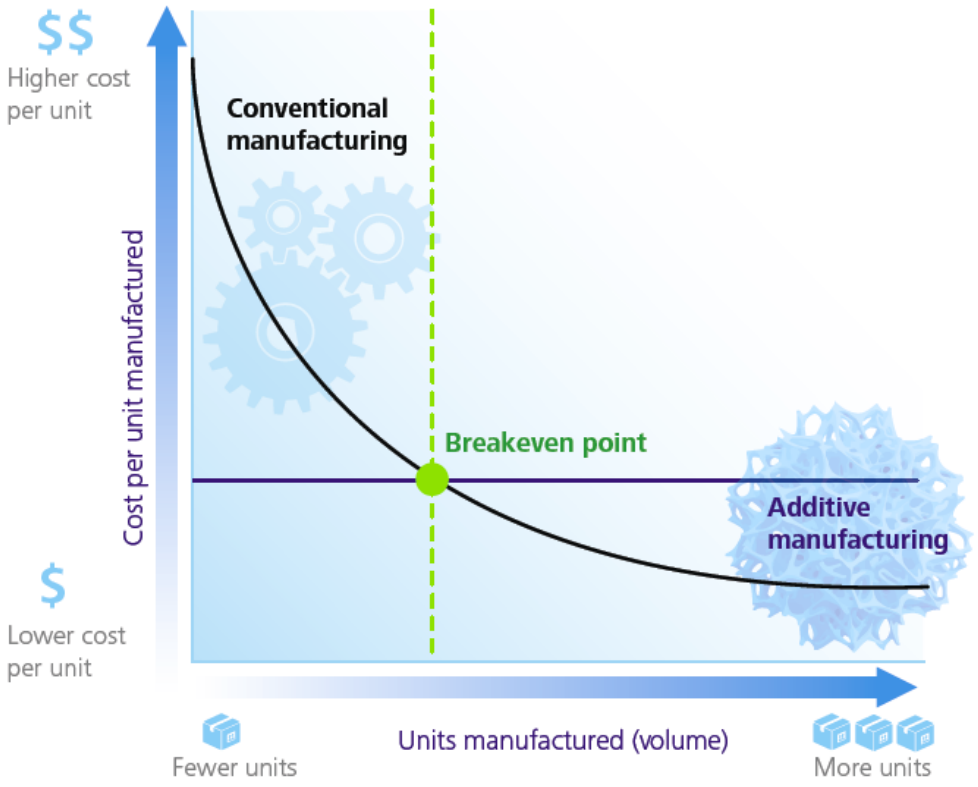

Figure 28: Breakeven between Additive and Conventional manufacturing (Cotteleer and Joyce, 2014)

Just like PCs, brought computing to non-traditional environments, 3D printing will bring manufacturing to non-manufacturers. When using Additive manufacturing it is recommended to identify low volume and where redesign is needed. The redesign should use the ability to create complex geometries and the reduction in part count. Furthermore, when the object requires a lot of material removed with traditional manufacture, it is an excellent candidate for cost effective with Additive manufacturing. As shown in Figure 29 the object will require a material subtraction of 75 percent or more during the machining process, hence it's a really good

candidate for additive manufacturing (Cotteleer and Joyce, 2014). The lead in time reduction, cost reduction, improved functionality and the increased ability to customize are some of the major benefits using Additive manufacturing (Neier et al., 2014).

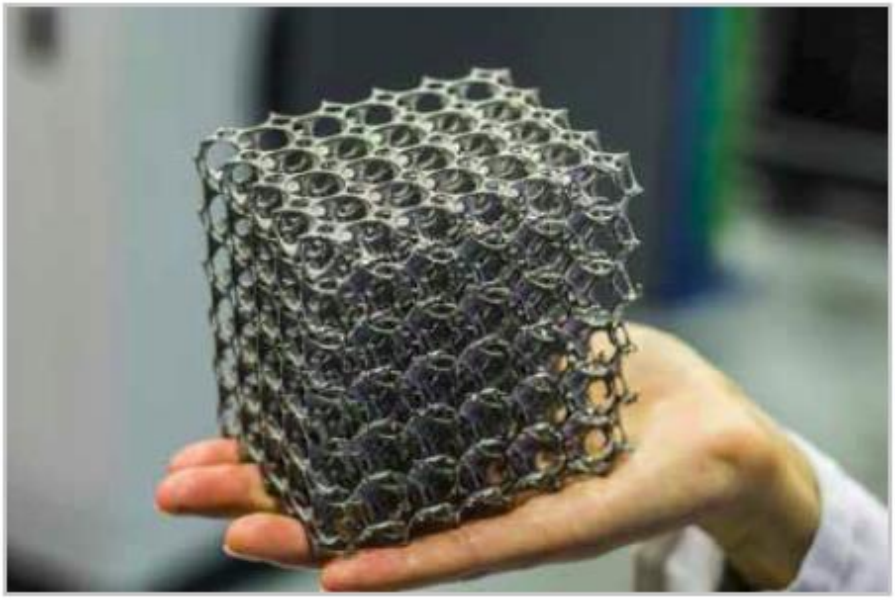

Figure 29: Complex 3D printed model (Cotteleer and Joyce, 2014)

2. Chapter 2 FDM Technology

Since a FDM printer will be used in the development of a shock absorber, the main focus will be on this technology.

2.1. Desktop FDM Styles

The FDM has evolved and grown to the point that this technology is now available for industries and individuals. There are some variations of desktop printers available but all of them work with the same method and components. There are four different styles of desktop printers that are described below.

- Cartesian: This style, demonstrated in Figure 30 is the most common on the market because the printer's mechanism and software are simpler. It works by moving on a 3 coordinate axes general X, Y, and Z in order to plot a point in a 3D space. The axes are linear and each one has a rail manipulated by sliding joints, belts or screws allowing it to position the nozzle anywhere in the working space (PrintSpace, 2014).

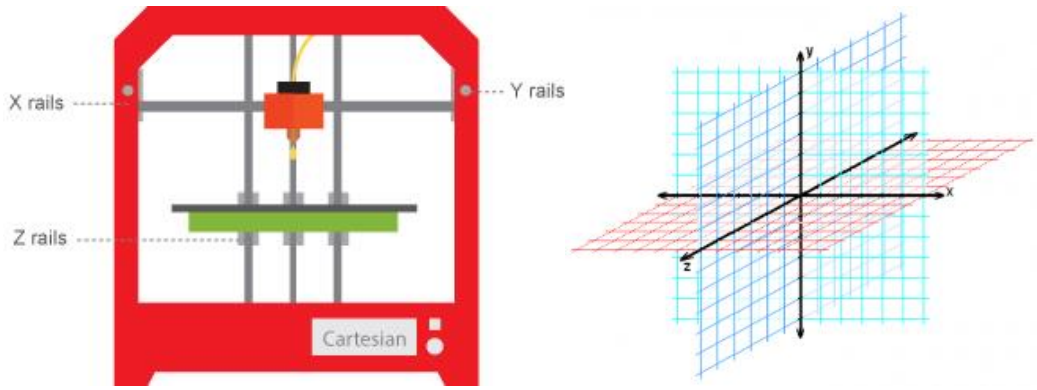

Figure 30: Cartesian Printer, and Cartasian Graph (PrintSpace, 2014).

- Delta: This system uses three runners on vertical rails and each one has an arm link to the extruder. These arms move vertically independent and are fixed to one another in order to maintain the extruder parallel to the platform. It estimates the extruder position or end point using trigonometric functions therefore the software that it uses its much more complex than the Cartesian style. The benefits are that it can build taller objects and it is space efficient. Also, the mechanical components are identical which makes the assembly process simpler (PrintSpace, 2014). The Delta System is showed in Figure 31.

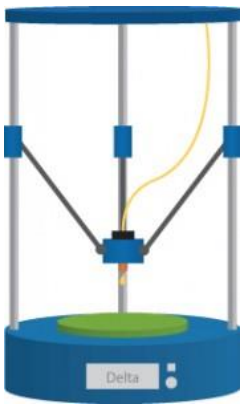

Figure 31: Delta Printer (PrintSpace, 2014)

- Scara: This system showed in Figure 32 gets its name from the abbreviation of Selective Compliant Assemble Robot Arm and it works with two long arms that bend at the joints in order to move the extruder around. The articulated arms change the extruder height depending on how far they are extended and therefore the software has to compensate by moving the platform up and down during each layer. This style is not too common but it is easy to build and the long arms allow the printing of bigger objects (PrintSpace, 2014).

Figure 32: Scara Printer (PrintSpace, 2014)

- Polar: As seen in Figure 33, these printers use only two axes instead of three like the others therefore it is much simpler to build. The X and Y axis are formed with the movement of two vertical rails connected to one horizontal that hold the extruder. In order to have a 3D space the Z axis is created by moving and rotating the whole platform. This allows a smooth extrusion but currently the complicated rotational geometry leads to many printing errors and complex software design. Due to the moving

platform it is also complicated to design heated build platforms that are required for some materials (PrintSpace, 2014).

Figure 33: Polar Printer (PrintSpace, 2014)

The main components of a desktop FDM printer, as shown in Figure 34, include the extruder, build, platform, control board and a display.

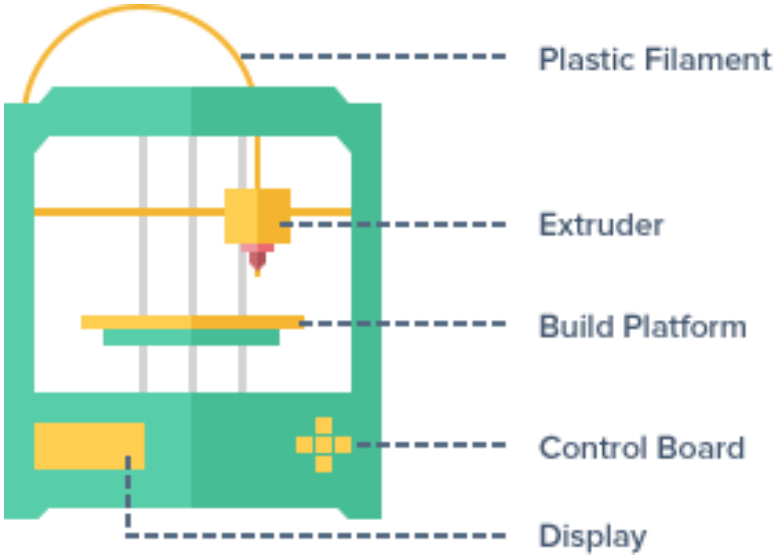

Figure 34: Printers main components (THRE3D, 2014)

2.2. Materials

As this technology develops also do the materials that can be used with it. One of the main limitations of FDM is the lack of material that can be used, however extensive research is being carried out in order to have a broader portfolio of usable materials. For example, Kibaran Resources, an Australian miner, has recently joined with 3D Group to investigate and patent

graphene and graphite for use in 3D printing. Graphene will significantly expand 3D printing applications since it is incredibly thin, strong, light, flexible and also an electrical conductor (Hagemann, 2014).

The materials are thin filaments of 1.75mm or 3mm thick and come in 1kg spools as shown in Figure 35. They are classified in four major groups the traditional, dissolvable, exotics, and other. Each group contains different materials that are explained below.

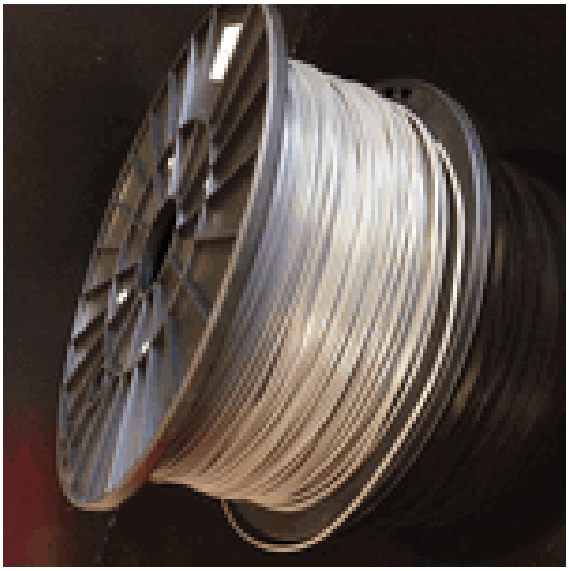

Figure 35: FDM 3D printing filament.(Smith, 2014)

2.2.1. Traditional

- PLA or Polylactic Acid: Is a thermoplastic polyester and it is made from ecofriendly plant matter, such as corn starch and sugar cane. Since it originates from an ecofriendly resource it makes it food approval (THRE3D, 2014). It is biodegradable because it reverts to lactic acid when left to break down, and also it can be recycled with hydrolysis back to monomers (Torlin, 2014). In 2010 this material was the second highest consumption of bioplastic of the world. In the industrial sector it is used in a vast variety of products from teabags to recipients (Torlin, 2014).

  The 3D printing filaments come in different colors and are relatively of low-cost. In the 1.75mm 1 kg spool there is 302 meters and in the 3mm there is 120.2 meters (Smith, 2014). The filament should be stored in dry places and not under stress because it will

break. It requires low temperatures to extrude and it forms a strong product (THRE3D, 2014). It is more brittle and has a harder surface than ABS. It requires low driving force and creates low pressure in the melt chamber due to its lower viscosity when molten. It is soluble in sodium hydroxide also known as caustic soda (Torlin, 2014). The low melting point is a limitation because the final product will deform at relative high temperature for example inside a hot car.

Extrusion recommended temperature: Minimum 150 and Maximum 250 °C.

Platform recommended temperature: Minimum 0 and Maximum 50 °C (THRE3D, 2014).

- ABS or Acrylonitrile Butadiene Styrene: This material is a thermoplastic derived from petroleum and it is one of the most used plastics now a days. This material is not ecofriendly and it is not safe for consumption. In industries it is mainly used in helmets and legos because it is a strong plastic (THRE3D, 2014). It doesn't have as fine surface detail as PLA but it is stronger and has a lower coefficient of friction. The plastic is resistant to many alcohols and acids, but it is soluble in Acetone (Torlin, 2014). It is easy to print and it requires high temperatures in order to extrude. It can be glued together easily by using neat acetone or an acetone/ABS slurry(RepRap, 2014). In the 1.75mm 1 kg spool there is 245 meter and in the 3mm there is 147.73 meters (Smith, 2014).

  Extrusion recommended temperature: Minimum 220 and maximum 275 °C

  Platform recommended temperature: Minimum 100 and maximum 130 °C (THRE3D, 2014).

2.2.2. Dissolvable:

- Hips or High Impact Polystyrene: This material is a petrochemical synthetic polymer and it is non-hygroscopic. It can be found in yogurt containers, Styrofoam containers, toys and CD boxes (THRE3D, 2014). It is very tough and can be recycled, also it can be painted and glued (Torlin, 2014).

  It has similar requirements to ABS during printing and it is manly used as a dissolvable support material. This is because HIPS dissolves easily in d-Limonene or orange oil see Figure 36 the white parts are HIPS and black is ABS (Torlin, 2014).

  Extrusion recommended temperature: Minimum 220 and maximum 240 °C.

Platform recommended temperature: Minimum100 and maximum 120 °C (THRE3D, 2014).

Figure 36: HIPS dissolving in Limonene (Smith, 2014)

- PVA or Polyvinyl Alcohol: It is synthetic polymer hydrolyzed from polyvinyl acetate and it is biodegradable and non-toxic. It is industrially used in fishing lures, production of textiles and several chemical purposes (THRE3D, 2014).

  It is ideal for use in a double extruder printer as a support material where complex geometries can be built and later the PVA can be dissolved with a warm water bath. When using this material special attention needs to be paid to the extruder temperature because if the temperature exceeds 210C the PVA will break down into tar which can clog or destroy the extruder (Torlin, 2014).

  Extrusion recommended temperature: Minimum 160 and maximum 200 °C.

  Platform recommended temperature: Minimum 0 and maximum 50 °C (THRE3D, 2014).

2.2.3. Exotics:

- Wood: This material is made from a combination of wood fibers usually a powder from recycled wood with thermoplastics. The product color can be from a light cherry to smoky wood depending on the extruder temperature (THRE3D, 2014). It prints with a sweet wood-like smell and the final product can be sanded and finished like if it was real wood as seen in Figure 1Figure 37. They usually have the same printing characteristics

as PLA and can be used on no heated platforms (THRE3D, 2014). It can be used on a variety of fake like wood products like wood panels on cars.

Extrusion recommended temperature: Minimum 170 and maximum 210 °C.

Platform recommended temperature: Minimum 0 and maximum 50 °C (THRE3D, 2014).

Figure 37: Object printed in wood like material

- TPE or Thermoplastic Elastomers: This material is also known as thermoplastic rubber and is a class of copolymers or a combination of polymers with both thermoplastic and rubber characteristics (THRE3D, 2014). It has a crosslinking microstructure which makes it flexible, bouncy and strong. It can be easily reprocessed and remolded and can be processed with thermoplastic methods (Spontak, 2013). The main characteristic is that it has the ability to be stretched to reasonable elongations, and when the stress is removed it returns back to its original shape (Spontak, 2013).

  Extrusion recommended temperature: Minimum 210 and maximum 230 °C.

  Platform recommended temperature: Minimum 30 and maximum 40 °C (THRE3D, 2014).
- Thermochrome PLA: This material will change of color when heated. When the temperature is below 29°C it has an opaque anthracite grey color and above this temperature it changes into a transparent color (Smith, 2014).

- Carbon fiber reinforced PLA: Is a mixed of PLA resin with 15% by weight Tenax small chopped carbon fibers. It has a high stiffness and resistance to bending. When printed the color is a dark glossy black and extruders around 190 to 210°C (Smith, 2014).

Figure 38: Object printed in Carbon PLA (Smith, 2014)

- UV sensitive ABS: It is like the normal ABS but when it is exposed to an UV source it rapidly changes into a vivid purple color and then with no UV source goes back to its normal white color (Smith, 2014).
- Ceramic filament: Is a mixture of ceramic powder and polymer blends and it is an experimental filament that required printer modifications and heat treatments in order to get it working (Smith, 2014).

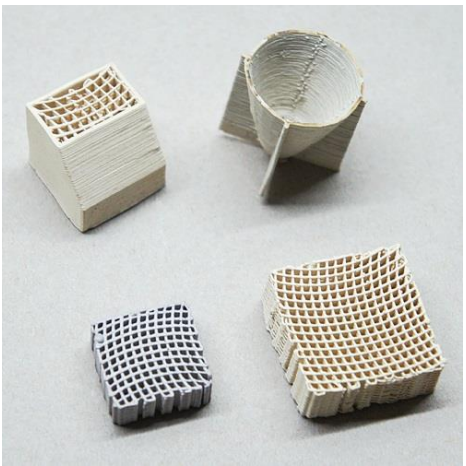

Figure 39: Objects in ceramic filament (Smith, 2014)

- Porous Lay filament or Lay-Fomm: Is a foamy material with a porous structure, it is a mixed of rubber elastomeric polymeric and PVA. It works by soaking the print object in water so the PVA is dissolved and only the rubber polymer remains as a micro porous flexible object. Parthy (as cited in Smith 2014) the inventor of this material says “Lay may be used for semi-permeable membranes and filters, artificial paper and future cloths”.
- Conductive Filament: This material is a mix of ABS material, carbon black, blends of carbon, fiber, and conductive masterbatch. It has exceptional mechanical strength, dimensional stability, high flow creep resistance and it can be used as anti-static, static dissipative, conduction of electric current, circuit boards and screen of electromagnetic interference shielding (Smith, 2014).

- Stone: The stone like material is made from finely milled chalk mixed together with thermoplastics. The material is brittle but it can be sanded and workable like a wood or stone product so it is great to use in architecture models and landscapes (Smith, 2014). When the material is extrude at low temperatures the print can feel smother and at high temperature more like a rough sandstone (THRE3D, 2014). The material tends to leave a pleasant texture overall and sometimes it may be needed an external fan in order to increase adhesion.

  Extrusion recommended temperature: Minimum 165 and maximum 200 °C.

  Platform recommended temperature: Minimum 0 and maximum 50 °C (THRE3D, 2014).

2.2.4. Others:

- Nylon: Is one of the newest 3D printing materials and it is a synthetic thermoplastic polymer. It is safe to be used in medical applications and also it can be dyed to change its color (THRE3D, 2014). The material is hard, strong, flexible, and gives an excellent surface bonding. The nylon is much lighter than ABS and PLA and also it is less brittle which makes it stronger (Taulman, 2014). The disadvantages are that it is stringier and it wraps more than ABS and PLA. It will not stick to aluminum or glass printing platforms so it is recommended to add garolite or blue painters tape (Smith, 2014). Since it is

hygroscopic it must be stored in dry places if not it will absorb the water from the environment and will have to be dry before being printed (Taulman, 2014).
Extrusion recommended temperature: Minimum 235 and maximum 260 °C.
Platform recommended temperature: Minimum 100 and maximum 130 °C (THRE3D, 2014).

- PET or Polyethylene Terephthalate: It is also known as Polyester and it is a synthetic polymer, made of purified terephthalic acid or dimethyl ester and monoethylene glycol (Johnson, 2014). It's the third most used plastic material; it's used in textiles, bottles and sails. It is recyclable and has a high mechanical strength. It is a lightweight plastic and is a very strong with impact resistant (Johnson, 2014).
  Extrusion recommended temperature: Minimum 210 and maximum 235 °C.
  Platform recommended temperature: Minimum 45 and maximum 60 °C (THRE3D, 2014).
- PC or Polycarbonate: It's a really strong and transparent synthetic polymer. It is made by a condensation polymerization resulting in a carbon that is joined to three oxygen's (Anther, 2013). It should be printed in ventilated environments and it has very rigid qualities. It is applied in many elements like cooler jugs and while it is cold it can be formed and bent (THRE3D, 2014). It's manly used to take advantage of its exceptional high impact strength and clarity (Anther, 2013).
  Extrusion recommended temperature: Minimum 270 and maximum 305 °C.
  Platform recommended temperature: Minimum 75 and maximum 95 °C (THRE3D, 2014).
- PC-ABS: It combines the flexibility and lower working temperatures of ABS with the strength of PC. This compound thermoplastic is commonly used in automotive parts and it creates high strength objects than can last longer (THRE3D, 2014).
  Extrusion recommended temperature: Minimum 220 and maximum 275 °C.
  Platform recommended temperature: Minimum 100 and maximum 130 °C (THRE3D, 2014) .

Beside these materials there is also interest in using this technology in the food industry and so far achieving prints in chocolate and ice-cream. Three students Donghyun, Bunker, and Kyle Hounsell from MIT have created a printer able to print ice-cream. It deposits thin layers of ice-

cream into a polyscience anti-griddle which features a -34°C plate that rapidly freezes the surface, although it can only print up to 10mm height because beyond that point the layer doesn't fully freeze (Krassen, 2014). In 2012 the company Choc Edge Ltd launched the first 3D commercial printer and recently it has released in the Chinese market its second version call the Choc Creator. It works with a stepper motor that extrudes chocolate out of a 10ml syringe at a maximum linear speed of 2000mm/min (Hipolite, 2014).

Figure 40: Chocolate 3D printer

2.3. Shock Absorbers:

A shock absorber or damper is a mechanical device designed to smooth out or damp shock impulses, and dissipate kinetic energy (Banginwar et al., 2014). The most common are pneumatic or hydraulic shock absorbers and are used in combination with cushions and springs. They commonly take the form of a cylinder with hydraulic fluid or air, and a moving piston in the inside. They are an important device used in automobiles and motorcycles suspensions, aircraft landing gear, and in many industrial machines (Banginwar et al., 2014).

Depending on their mechanism and usage there are various types of shock absorbers. Some of these types are the air shock absorber, the damper shock absorber, the mono tube shock absorber, the twin tube shock absorber, the spring shock absorber and the MR fluid shock absorber

(Hassam, 2011). The type of shock absorber chose for this project is the spring shock absorber which uses the effect of a spring to absorb the shocks as shown in Figure 41. The tighter the spring coil is the stiffer the shock absorber will be.

Figure 41: Spring shock absorber

3. Chapter 3 Design and Develop

The rapid growth and development of 3D printing is allowing us to create and build things that were never thought possible. It is being used in many industries and the overall market size was estimated at 2$ billion in 2012, and its growing at a compound annual growth rate of 14.2% (Neier et al., 2014). The improvements on FDM technology have led to more sophisticated and cheaper printers allowing hobbyist and regular customers to experiment and work with these printers. In order to explore the benefits and capabilities of this technology a spring shock absorber will be build using the new Up Plus 2 printer.

3.1. 3D Printer Up Plus 2

The Up Plus 2 shown in Figure 42 is a commercial 3D printer made by 3D Printing Systems. This plug and use home 3D printer is friendly and works with fused deposition modeling technology. The filament is extruder through a hot nozzle that moves in the Y axis, while the platform moves in the X and Z axis allowing three degrees of freedom in order to build up any 3D object. It has a built in heated platform which allows printing a wide range of materials and avoiding warping. Some of the benefits and innovations from this printer, which make it user friendly, are the automatic platform leveling along with automatic platform height detection. It's always required to have the platform level to avoid any warps and the height must be the specific depending on the material being used. The auto level and height detection make the printing setup much easier but it can also be done manually if needed.

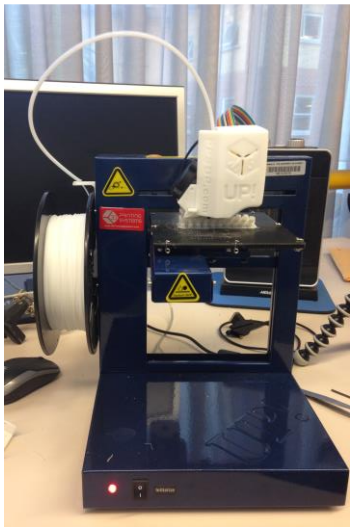

Figure 42: Up Plus 2 3D printer

In order to start designing any object the user must first know the specifications of the printer going to be used. For the Up Plus 2 the specification are found in the user manual and are shown in Table 2. These specifications show a print bed size of 140x140x135mm, which means the object design can't be bigger than that. If the object is bigger it should be assembled or glued in different components. Another solution is using the 3DPrintTech application that has just being released by CCtech. This application works as a CAD plugin that is able to divide the large object into small connectable components within few minutes (Krassenstein, 2014).

This printer is not an open source 3D printer and therefore it comes with its own software. The software is included and it automatically calculates the required support material. It reads any STL file which then can be modified to start printing out, these modifications include.

- Scale, Rotate, Move & Print
- Supported File Types: STL
- Extrusion temperatures 260 and 200 degrees
- Print Preview with material usage and time estimates
- Automatic placement
- Repeat last print
- Rotate, Resize, Scale, Move 3D object
- Select layer thickness (0.15mm to 0.40mm)
- Select print speed vs. quality
- Variable fill of models with honeycomb fill.
- Fine to large honeycomb mesh
- Smart Support
- Automatic Support material angles, 10 to 80 degrees

Table 2: UpPlus2 specifications

Printing Material	ABS or PLA
Material Colour	White
Layer Thickness	0.15—0.40mm
Print Speed	(fine) 10— (fast) 100 cm^3/h
Print Bed Size	140×140×135mm
Printer Weight	5 KG (11 lb)
Printer Size	245 × 260 × 350 mm
Extrusion Temperature	ABS: 260-270c PLA:200
Platform Temperature	ABS: 100c PLA:50c

3.2. Designing for 3D printing

Since 3D printing is not like the conventional manufacturing process there are some aspects that need to be considered. The object that's going to be built has to be designed according to the material that will be used and the specifications of the machine. A basic design guide recommended to follow for a successful 3D printing is shown below.

3.2.1. 45 degree rule:

Since FDM builds the object layer by layer, the 45 degree rule has to be consider where overhangs that are greater than 45 degrees will need support material. The support material is required because gravity will bring the layer down if there's not any support. This support material can be built on the interior of the piece or outside depending where it's needed (Kaziunas, 2013). Hence, if the angle is greater than 45 degrees the support material should be used or the design should be modified. In Figure 43 it can be clearly seen if the angle of the model is bigger than 45 degrees it will be likely to fail.

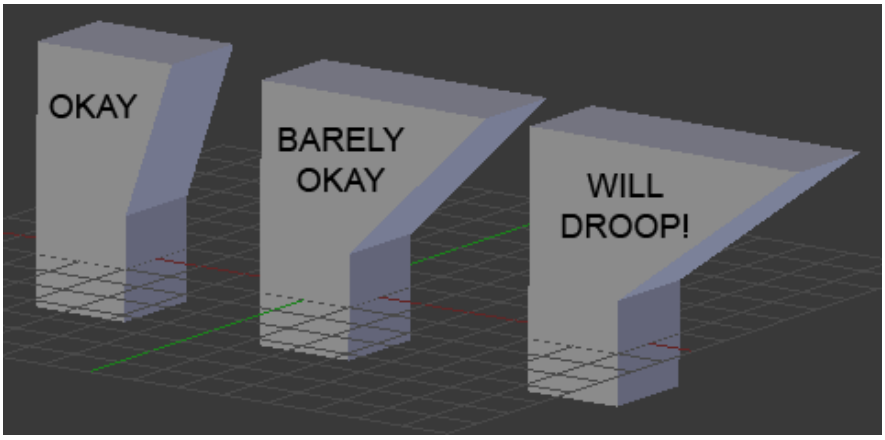

Figure 43: 45 degree rule (Kaziunas, 2013).

3.2.2. Design to avoid support material

It's recommended to design the model in a way it won't need support material because it creates kinks on the surface of the object when it is remove. The support material can also be time consuming to remove and it will use unnecessary material. Therefore, the design should be done to minimize the support material or use methods to add custom support. For example, the "mouse ears" that are helper disks and cones designed into the model to help it print without the use of computer generated support material (Kaziunas, 2013).

3.2.3. Know your printers limitations

When printing pieces with small features make sure to know the printer limits in order to know if it's capable of achieving those specifications. One important variable is the thread width which is determined by the diameter of the printer nozzle. Most FDM printers have a 0.4mm which means that the circle drawn by the printer is always two thread widths deep so 0.8mm thick (Whiston, 2014). The smallest feature it can be made is double the thread width and this is known as the rule of thumb (Kaziunas, 2013).

3.2.4. Fit tolerances for Interlocking Parts

Objects with interlocking parts need to have the correct tolerances in order to work as intended. Its recommended to use 0.2mm offset for a tight fit and 0.5mm or bigger offset for a lose fit (Kaziunas, 2013). Also, a non-manifold model won't be able to be made because the edges of the model must not be shared between more than two faces (Whiston, 2014).

3.2.5. Improve thread width

When the object needs very thin features it is recommended to design the walls of the model to be one thread width thick. For a better strong surface it should be designed with a minimum thickness of 1mm (Whiston, 2014).

3.2.6. Orient for the best resolution

On the FDM printers the X and Y resolution are determined by the thread width so only the Z resolution can be controlled. This Z resolution should be oriented depending on the model, hence obtaining the best surface finish and fine features. If it is a complex model the direction of printing ,vertical or horizontal, will have a significant impact (Kaziunas, 2013). Also the model can be sliced into pieces for later re-assemble as shown in Figure 44.

Figure 44: Sliced and assemble for best orientation (Kaziunas, 2013)

3.2.7. Orient for stress

If the object being printed will have a force applied to it the orientation will also have a significant effect. In order to keep the piece from breaking when the force is applied it should be oriented with the print layers perpendicular to the point of the pressure being applied (Kaziunas, 2013). Since its build up layer by layer there will be a weak point between each bond, so if the force is parallel it may break these bonds.

3.3. Design of the Spring Shock Absorber

The design of the shock absorber is limited by the Up plus 2 printer capacity, shown in Table 2, and the materials being used. The spring shock absorber was designed using SolidWorks and

taking in consideration the 3D printing guides shown in the previous section. It consists of a total of eight components which will be 3D printed and then assembled into one. Two of these components will be printed in rubber-like material (TPE) and the rest on ABS. The rubber-like material will be used for the bump stopper and a seal, the ABS will be used for one spring, a cylinder, a piston, two caps, the locking ring and a preload adjuster.

In order to test the 3D printed spring shock absorber a cam and follower will be designed to move the spring up and down, simulating a real application. The cam will be connected to an electric drill that will move the follower, and consequently push the spring up and down. The shock absorber will be screwed to an acrylic sheet as shown in the assembly sketch in Figure 45, which will keep one side of the shock absorber fixed. In order to observe all of its components an exploded view is shown in Figure 46. The total number of components required is shown on Table 3. All of these components will be 3D printed except the acrylic sheet and the screws.

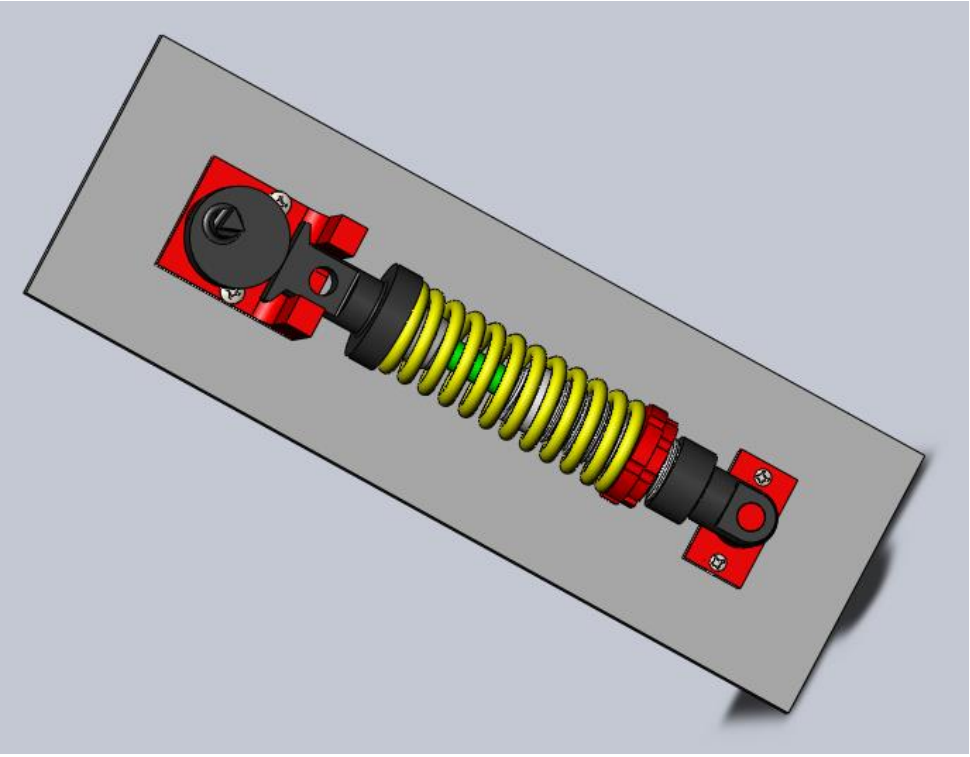

Figure 45: Assembly sketch

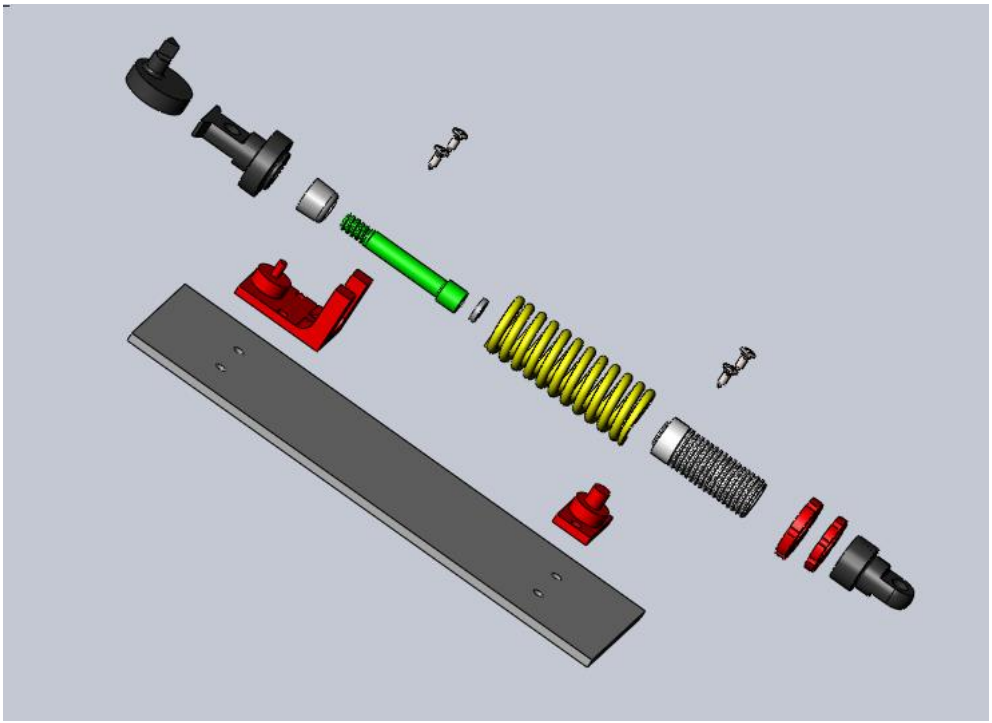

Figure 46: Exploded view of shock absorber system

Table 3: Components for the system

ITEM NO.	PART NUMBER	QTY
1	Spring	1
2	Cylinder	1
3	Locking ring	1
4	Preload adjuster	1
5	Piston with rod	1
6	Cap	1
7	Cap with follower	1
8	Cam with Shaft	1
9	Bump stopper	1
10	Seal	1
11	Supports	2
12	Screws	4
13	Base	1

3.4. Design of components

3.4.1. Design of spring

The spring is the main component of the shock absorber and it is defined as an elastic body that deflects when loaded, and recovers to its original shape when the load is removed (Khurmi and Gupta, 2005). Springs have different applications for example to control motion in machines, reduction of transmitted forces as a result of impact or shock loading, to storage energy, measurement of forces, and dissipate shock and control oscillations (Khurmi and Gupta, 2005). There are many types of springs with different shapes, for different uses and applications.

A coiled compression spring will be used for this shock absorber. These type of springs are made up of a wire coiled in the form of a helix and are mainly used for compressive loads (Khurmi and Gupta, 2005). Figure 47 shows the sketch of the spring which has a constant pitch of 8mm. It also has a spring end preparation to provide uniform force distribution around the end of the coil. This end preparation is a squared and ground ends, where the end turns are squared and the ground perpendicular to the helix axis. This ensures that the axis of the force applied is aligned with the center line of the coil (Norton, 2000). With this the spring has 9 active coils and 2 inactive coils. The specifications of the spring are shown in Table 4, and it has a spring rate of 5.8. The spring rates between 5 to 10 are easy to manufacture, higher than 10 are cheap, large and imprecise. If the spring rate is below 4 they are compact and difficult to make, which will require heat treatment before and after coiling (Lozzi, 2014). High spring rate indicates a voluminous spring, and the spring stiffness varies inversely with the third power of the spring rate (Norton, 2000). The decimal factor is 0.3mm which is the minimum space between wire coils when the spring is loaded. When the spring is loaded it should never work to the packed length that's why the minimum length is higher than the packed length (Khurmi and Gupta, 2005).

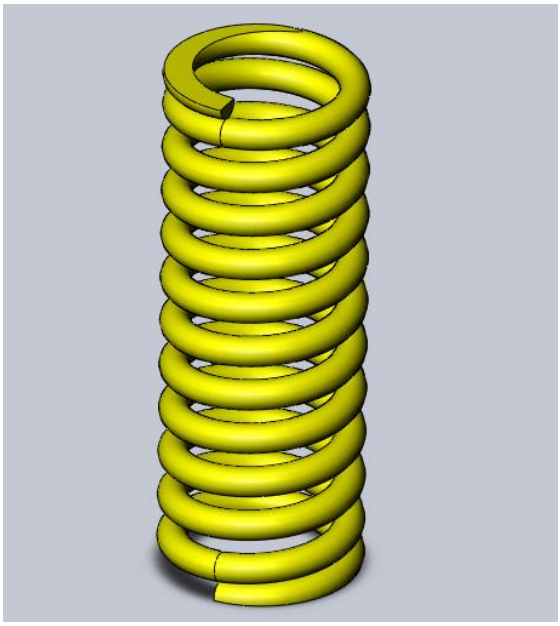

Figure 47: Sketch of spring

Table 4: Spring specifications

Helical Spring of circular wire		
Description	**Variable**	**Value**
Mean diameter of the spring coil	D [mm]	29
Diameter of the spring wire	d [mm]	5
Number of active coils	n [units]	9
Number of inactive coils	ni [units]	2
Spring index	C [D/d]	5.8
Pitch of the coils	p [mm]	8
Free length	Lf [mm]	90
Packed length	Lp [mm]	55
Decimal factor	s [mm]	0.3
Minimum length with load	Lm [mm]	68.5

3.4.2. Design of cylinder

The cylinder is a round tube that acts as a guide for the piston and prevents the spring from buckling. When the diameter of the spring is small compared to the length, the spring buckling can occur (Khurmi and Gupta, 2005). The outside diameter of the cylinder is almost the same of the inside diameter of the spring to prevent the buckling. Although, because the spring tends to grow in outside diameter as it is compressed, the space must be big enough to prevent it from

jamming. The cylinder also has a thread in which the locking ring and preload adjuster will move. This male thread is wrapped around the outside of the cylinder and it is a helical structure used to convert between rotational and linear movement or force (Bhandari, 2007). The thread had to be designed based on the Up plus 2 specifications, therefore they couldn't be fine threads. In order to select the correct thread for the job, three different types of bolts and nuts where 3D printed as shown in Figure 48, each one with different type of thread. These types of threads are the buttress thread, square thread form, and the acme coarse thread. The results showed that either the buttress thread or the coarse thread could be used; only the square didn't work due to the support material in between each thread.

Figure 48: Type of threads on bolts and nuts

The chosen thread for the design is the coarse thread with a 3mm pitch for the 24mm diameter cylinder, which allows a precise movement in order to adjust the spring. The same thread is also used in the assembly of the shock absorber for screwing the two end caps. The final sketch of the cylinder is shown in Figure 49, on the upper end the cap will be screwed, and the bottom end has a smaller internal diameter in order to lock the piston and prevent it for coming out.

Figure 49: Sketch of cylinder

3.4.3. Design of piston, lock ring and preload adjuster

The piston moves inside the cylinder and it has 0.2mm of offset with the cylinder in order to have a solid and tight movement. The piston is connected to a rod, which has a thread at the end in order to screw the bottom cap. Figure 50 shows the design of the piston with the rod that will be printed in green ABS and the end has a male thread with 3mm pitch in order to screw the bottom cap. The round seal shown at the left of Figure 51 will be printed in TPE and glued to the head of the piston to allow liquid inside the cylinder. The bumper stopper shown at the left of Figure 51 will also be printed in TPE and will go at the bottom of the piston to prevent it from bottoming out.

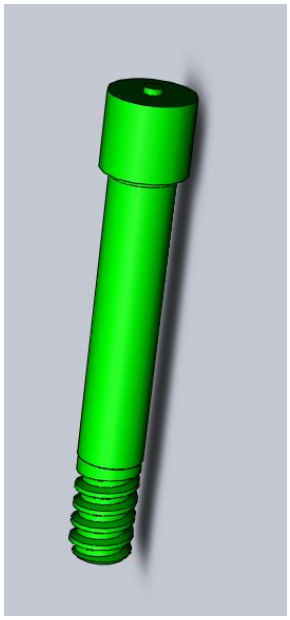

Figure 50: Sketch of Piston with rod

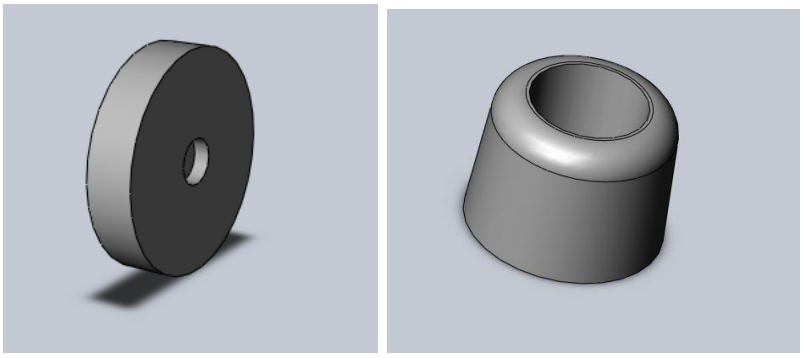

Figure 51: Seal (left) and bump stopper (right)

The preload adjuster and locking ring are two round rings with external groves for adjustment. They have an internal thread with an offset of 0.5 from the male thread in order to have a tight interlocking and smooth screwing movement. The lock ring is only smaller in diameter compared to the preload adjuster. The lock ring prevents the adjustment ring from moving, therefore maintaining it fixed in the position that's required. The preload adjuster is shown in Figure 52 to the left and at the right the locking ring. Both rings will be printed on red ABS.

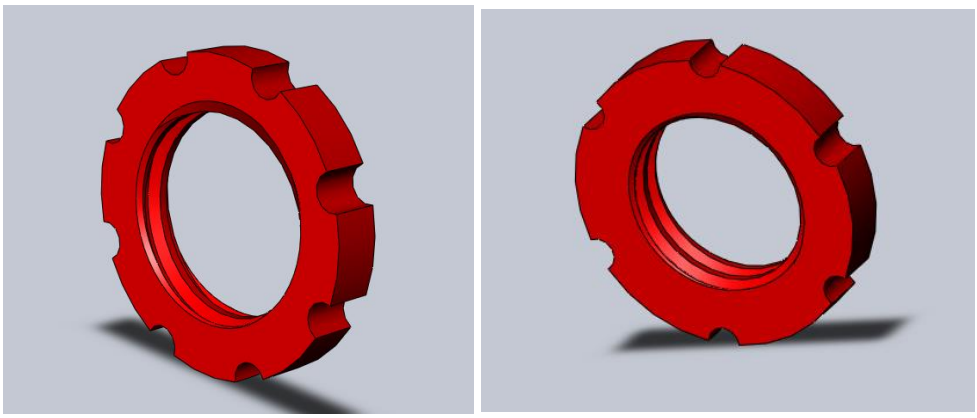

Figure 52: Preload adjuster (left) and locking ring (right)

3.4.4. Design of caps

There are two caps that go at each end of the shock absorber. The lower end cap shown in Figure 53 has a female thread with a 0.5 offset that's screwed into the piston rod. It has a simple saddle where the end preparation of the spring is compresses adequately. The upper cap has a female thread with a 0.5mm offset that's screwed into the cylinder as shown in Figure 54. Both caps have a round finishing with a round hole for installation.

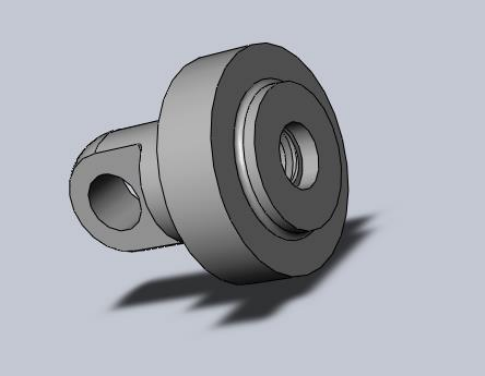

Figure 53: Bottom end cap

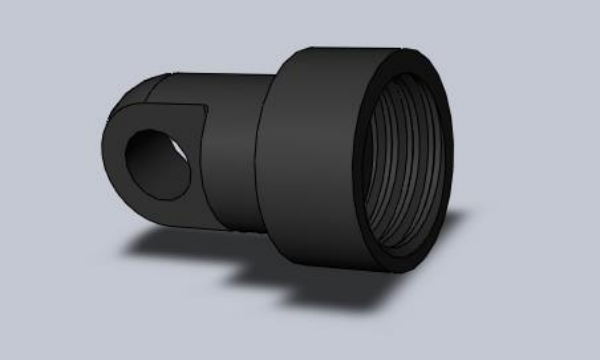

Figure 54: Top end cap

3.4.5. Design of Cam and Follower

The cam and follower is a device that is able to convert rotary motion into linear motion. The cam is a machine element with a curved outline that is fixed to a rotating shaft and due to the reciprocating motion it gives a predetermined specified motion to another element called the follower (Wang, 2006). There are different shapes of cams such as: oval, round, heart shaped, egg-shaped, ellipse, eccentric, hexagon and snail. The follower is always in contact with the cam and depending on the surface in contact they can be classified as knife edge follower, roller follower, flat faced follower, and spherical faced follower (Phakatkar, 2005).

In order to test the spring shock absorber an eccentric cam with a flat-faced follower has being selected as shown in Figure 55. The eccentric cam is also known as a circular disc cam because it is a round disc. This circular disc is mounted eccentrically on a camshaft where the lift provided is twice the eccentricity (Phakatkar, 2005). The circular disc shown in Figure 56 has 7.5mm eccentricity of cam, therefore the lift will be 15mm. In order for the device to work an electric drill will be used, as it will act as the motor for the system. The drill will be connected directly to

the shaft of the cam which has a triangular profile at the end for a quick connect system. As the drill moves it will move the eccentric cam that will lift the follower, consequently the spring will be compress 15mm on each cycle.

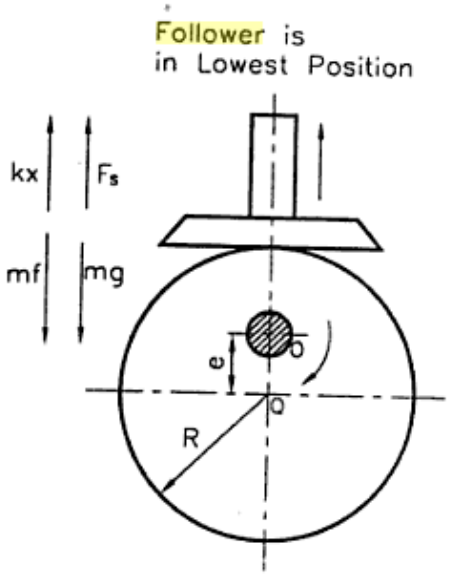

Figure 55: Eccentric cam with a flat-faced follower

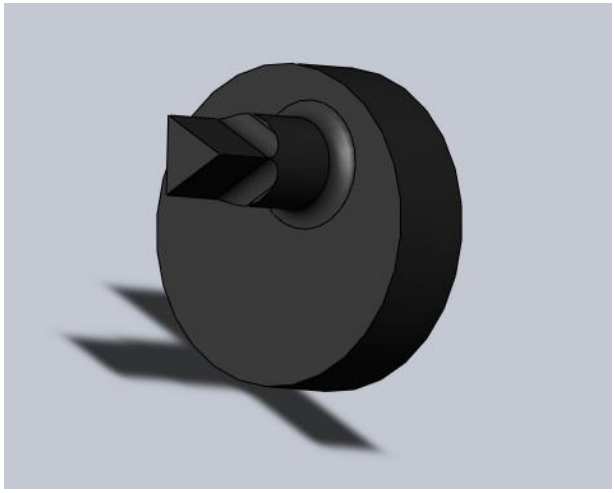

Figure 56: Eccentric cam with shaft

The follower is a modification of the bottom end cap that connects to the piston rod, therefore by changing the caps it can be used with the cam mechanism. It is the same design but with a flat faced end as shown in Figure 57. This is a radial follower where the path of motion of the follower is along the axis passing through the center of the cam (Phakatkar, 2005).

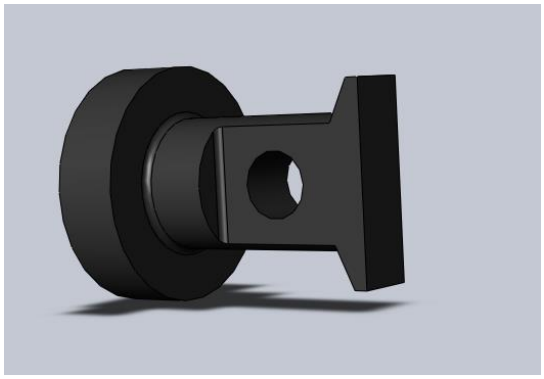

Figure 57: Bottom cap with flat-faced follower

The last components are two stands supports for the shock absorber and cam. These supports will be fixed to a cast acrylic sheet using four pan head screws. The first support shown in Figure 58 has two holes for the screws and a shaft that connects to the hole of the upper cap. Once the shock absorber is in position a pan head screw with a washer will be screwed on the center of the shaft keeping the upper cap fixed. The second stand support has two holes for the screws and a shaft where the eccentric cam will be connected allowing it to move freely. This stand also has two square columns on the end edges that will act as a guide for the cam mechanism, and to keep the shock absorber straight and secure during the movement.

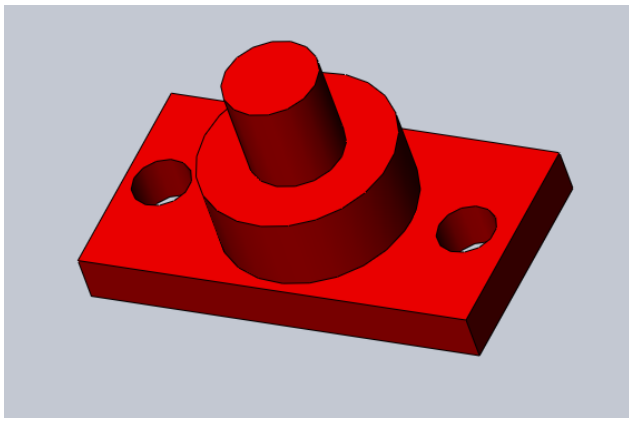

Figure 58: Upper stand support

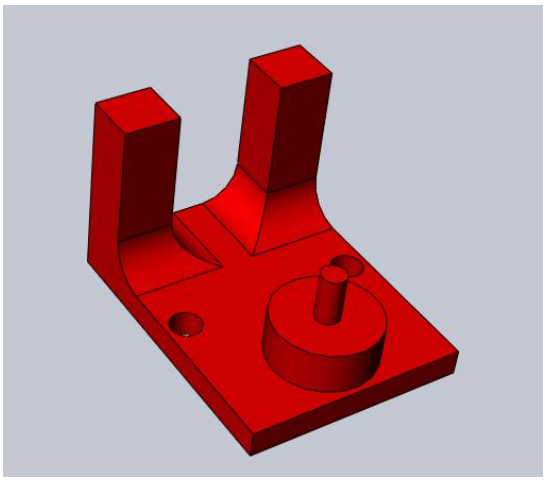

Figure 59: Cam stand support

For further information and dimensions on the components presented in this section refer to the appendix.

4. Chapter 4: 3D Printing

The Up Plus 2 printer is a friendly user printer that came out around 9 month ago with a retail price of 1950$ AU. Since then the printer has been reduce in price and can now be purchased for around 1300$ AU, this clearly shows how fast this technology is changing and becoming more accessible. The process in order to 3D print using the Up Plus 2 printer is described below.

4.4. Process

In order to start printing with the Up Plus 2 a sequence of recommended steps are shown below:

- The printer has to be set up properly and the user manual must be read beforehand.
- Install the Up software.
- The CAD design must be safe on STL format and then open on the Up software.
- Set the object in the desired position by rotating and moving the model, it can also be scaled to make it fit in the built in platform or to make it bigger.
- Connect the USB cable to the computer and initialize the printer, it will make the printer beep and center the platform.
- Load the filament reel and feed it through the filament guide and into the print head.
- Clean the perfboard using a spatula to scrape the surface, and set it on the platform securing it with the clips.
- Connect the cable and sensor to the printer and set the auto level and height of the platform.
- Click on the 3D print icon and select maintenance, choose the type of material ABS or PLA and extrude the filament. Also preheat the platform if needed.
- Click on the print icon and select preferences
- The preference window lets the user choose different settings:
    - Z resolution: The height of each layer can be selected between 15, 20, 25, 30, 35, and 40mm. The bigger the layer height the less bonding it will have but it will take less time to print.
    - Fill: The object's internal fill can be selected as shown in Figure 60 from left to right solid, semi-solid, semi-hollow and hollow honeycomb. The solid option will make a nearly solid, which is stronger but takes longer time to print. It can also print shell that

will print only the external shell without internal honeycomb, therefore the object will be fragile. The last option is surface, which prints the model with one layer thick and no internal fill, it will also not create a flat bottom surface or the top flat surface.

Figure 60: Type of fills

- Support: The angle for the support to build on the piece can be changed between 10 to 80 degrees but it is recommended to use at least 45 degrees, due to the 45-degree rule previously mentioned. The density of the support and area can also be modified.
- Stable support: It will create a more rigid support but will be more complex to remove it from the model.

- In the print window the user can also choose some options described below:
  - Quality: The print quality can be selected between fine, normal and fast. The normal is the average quality, the fast is a draft quality but takes less time to print, and the fine is the best quality but takes longer time.
  - Pause: The print can be stopped at a defined height in order to change of color or to insert objects.
  - Heat platform: After the print is completed the user can keep the printer heated for 5 minutes or up to 60 minutes for a better cooling down and in order to avoid deformations on the model.
  - Unsolid model: This function is to allow printing STL files that are not perfect, meaning it doesn't have a fully enclosed surface.
  - No raft: It will print the model without a raft.

- Click OK and a window will let you know how much material will be used and how long it's going to take, after that the print will start and the USB cable can be unplugged from the computer.
- Once the print is finished it will beep. Carefully proceed to remove the clips and slide the perfboard out of the platform.
- Carefully slide the spatula under the model and slowly wiggle it back and forth until the model is loose.
- Finally carefully remove the raft and support material from the model.

Remember to always use gloves and the safety equipment to prevent burns and cuts.

4.5. Printing with ABS

All the component needed where successfully 3D printed on ABS as shown in Figure 61, following the previously mention steps. The ABS is extruded around 260 °C and with a heated platform of 100 to 105 °C to avoid warping. In order to make sure the shock absorber is strong enough to work properly almost all the components were printed using a 0.20mm layer resolution, which gave a nice surface finishing and an excellent bonding between each layer. Also, the door vent was kept closed at all times because when it's open the air will weaken the layers bonding. The components were printed with red, green, black, yellow and white ABS. Before printing it was necessary to preheat the platform, which takes around 20 minutes. In order to speed up the heating process a cloth can be placed on top of the platform that will reduce the heat dissipation.

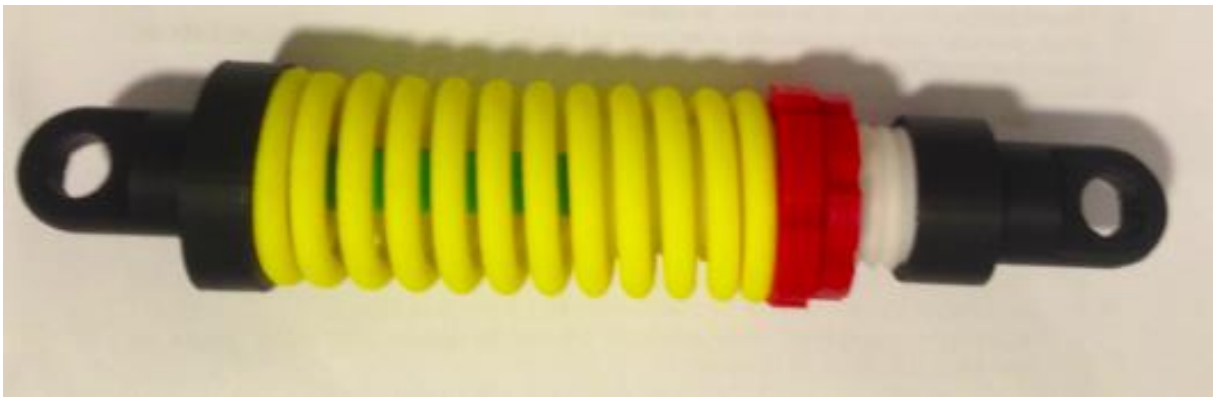

Figure 61: 3D printed shock absorber in ABS

There were some difficulties while printing the spring and the caps that were the most complex components. When the caps were printed vertical and upside down the surface finish at the end was rough and had kinks from the support material. The surface was sanded in order to fix this problem, but it didn't work because when sanding color ABS the tone of the ABS changes as shown on the left side of Figure 62. The best solution was printing it vertical, but not upside down, and then carefully removing the support material from the inside female thread using acetone to weaken the support material as shown to the right of Figure 62.

Figure 62: 3D printed cap with sanded surface (left,) and upside down printed cap (right)

The spring was the most complex part, which took several attempts to accomplish the printing. The spring is also the largest component so the platform needed to be really hot in order to avoid the edges lifting up during the printing causing the model to warp. This happens because the ABS comes out the extruder in an expanded state and when it cools it shrinks, so the hot platform will help the model to cool evenly. It was printed vertically and horizontally in order to see which option gave the best results. The vertical was easier to remove from the platform because there was less surface area in the platform, but it came out with more support material that left more kinks on the surface of the spring when it was removed. The time to remove the support material using the hands and scalp was also much longer. Therefore, the best way to print was horizontal as shown in Figure 63, although it had more surface area on the platform it just needed the platform to be really hot to avoid warp.

Three spring where successfully printed with different fills. These prints where made with a fine quality which is a print speed of 10cm^3/h, a layer resolution or thickness of 0.25mm with solid fill, semi-solid, and semi-hollow honeycomb fill. The ABS is a tough and rigid material but it turned out to work really well as a flexible spring where it can compress when a force is applied and then returns to its free length. The spring has small kinks in the flat size where it was touching the Raft when being printed. These kinks were reduced by carefully sanding the surface.

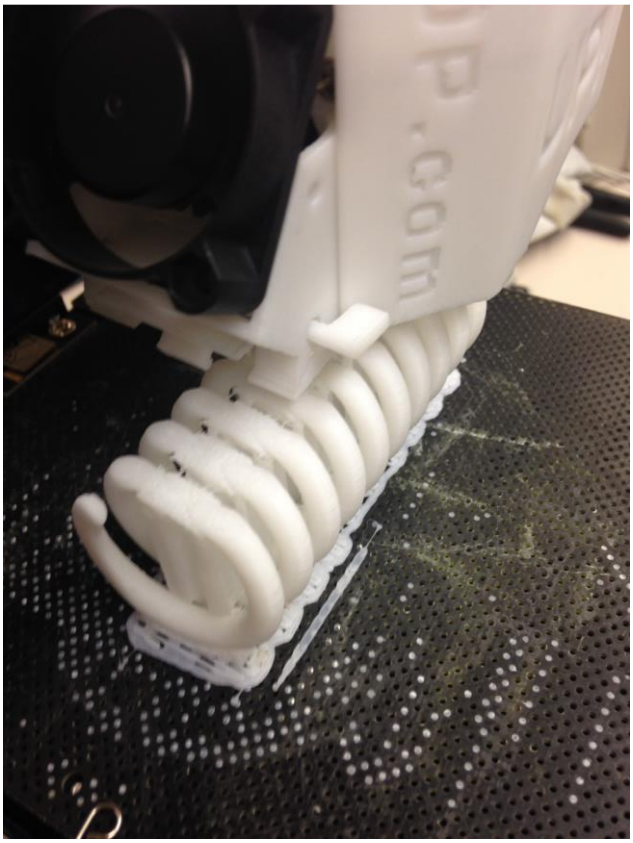

Figure 63: Horizontal 3D print spring

White ABS was the easier to work with compare to the colors ABS. The color ABS was pretty similar but it needed better room temperature control, and any breeze could deform the model much easier than when using white ABS. This can be seen in Figure 64 where the red ABS spring shifted during the print due to a change in the environment.

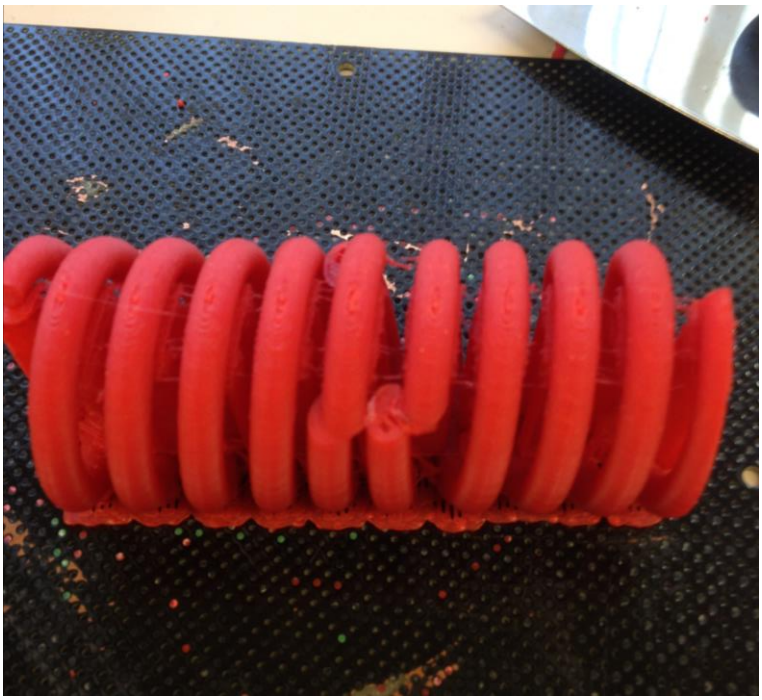

Figure 64: Shifted 3D print spring

When changing the filament always make sure to cut the end of the new filament before inserting it to the extruder head because it can jam the drive gear. Also, make sure the nozzle is clean in order to get a nice even layer all the time. The sign of a blocked nozzle is when printing the fine raft crass hatching and the lines are uneven or when extruding the filament it comes out at an angle.

4.6. Printing with TPE

The rubber like material (TPE) is a new material with flexible properties that was used for the seal and the bump stopper. There was a major difficulty printing this material with the Up plus 2 because the Up software doesn't allow changing the extruder temperature. The software only allows the user to set the extruder temperature to 200 °C for PLA and 270 °C for ABS, whereas TPE needs around 230 °C. Therefore, it is very tricky and technically demanding to print it correctly.

Since the PLA temperature setting was too low the TPE wouldn't even extrude, so the ABS setting had to be used. After numerous experiments using the ABS setting it turn up to work really good and the models were successfully printed. They resulted as expected; when the object was under stress it deformed and then return to its original shape ones the stress was removed. In

order to successfully print TPE on the Up plus 2 some printing settings had to be configured, which are shown below.

- First of all the table height had to be manually set in order to work because the material can jammed the extruder at the normal ABS height. The space between the nozzle and the platform is recommended to be 0.3mm. The simplest way to get the correct height that worked after various prints was to use the automatic height detection and after that subtract 0.3mm. After the auto height is detected the measurement will appear in the printing setting window, it's usually 135.43mm so it was changed to 135.13mm.
- Make sure the platform is leveled.
- The recommended platform temperature is 30 to 40°C so the platform should not be preheated. Also, do not program the platform heat to continue after the print.
- Since the filament is slightly sticky it may get stuck when being unwind so it should be manually feed though the filament guide tube to enable a smooth feed. If the material doesn't run smoothly through the guide, some WD-40 can be added in the guide so it flows properly.
- It comes out of the extruder as a viscous liquid so it's recommended to use only semi-hollow or hollow fill. Also, the model will be more flexible when the hollow fill is used compared to the solid fill.
- The resolution recommended is of 0.25mm, and the quality should be normal. When the fast speed was used the model was distorted and with holes because the extruded material was not fast enough for the moving speed. Whereas, in fine quality the speed was too slow and sometimes due to the high temperature the material accumulated in some parts which deformed the model.
- The extruder vent door should be closed because since there is more distance from the platform to the extruder the air from the vent will push the extruded filament resulting in a less precise layer deposition.
- If the final model has a bit of yellowish color the overall temperature was too hot. To fix this the extruder vent door can be open halfway or it's better to lower the room temperature. An external ventilation or air-conditioning could be used to lower the

temperature. As shown in Figure 65 the printed TPE tests with different temperatures, the one to the left is a bit yellow and as the temperature lowers it gets whiter and translucent.

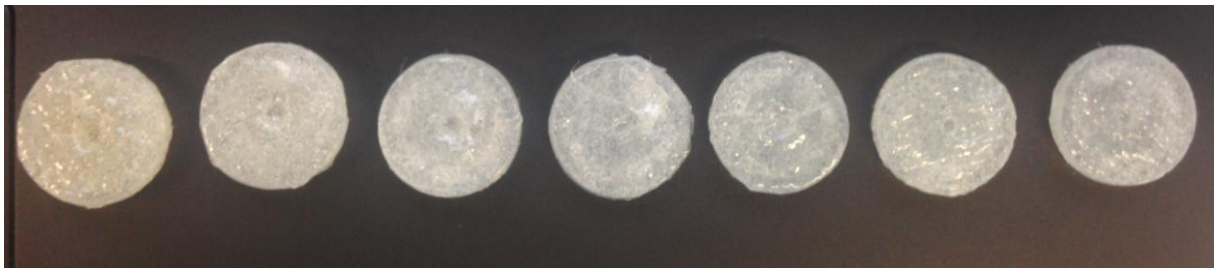

Figure 65: Temperature tests on TPE printing

- The design should be done to avoid support material.
- The material has a good adhesion to the perboard so there's no need of adding any additives.
- The no raft option should be used. It has to be printed with no raft and any material that needs to be removed will have to be cut off with the cutter. Using the no raft option will result on a rough surface finish due to the contact with the platform because it solidifies with the form of the perboard. In order to solve this problem BuildTak adhesive printing sheets where used. The BuildTak sheets allow having a smooth surface finishing when printing raft-less, because it provides a flat surface as shown in Figure 66. The material stuck really well to the BuilTak sheet and therefore no further modifications are required. In order to use the BuilTak sheet only a few steps shown below must be done:
    - Scrap both sides of the perboard and make sure it is clean.
    - Remove the backing sheet of the BuildTak and stick it to the perboard.
    - The BuildTak has a thickness of 0.3mm so this must be taken into account when printing. Therefore, in the printing setting window 0.3mm more should be subtracted to the total height.

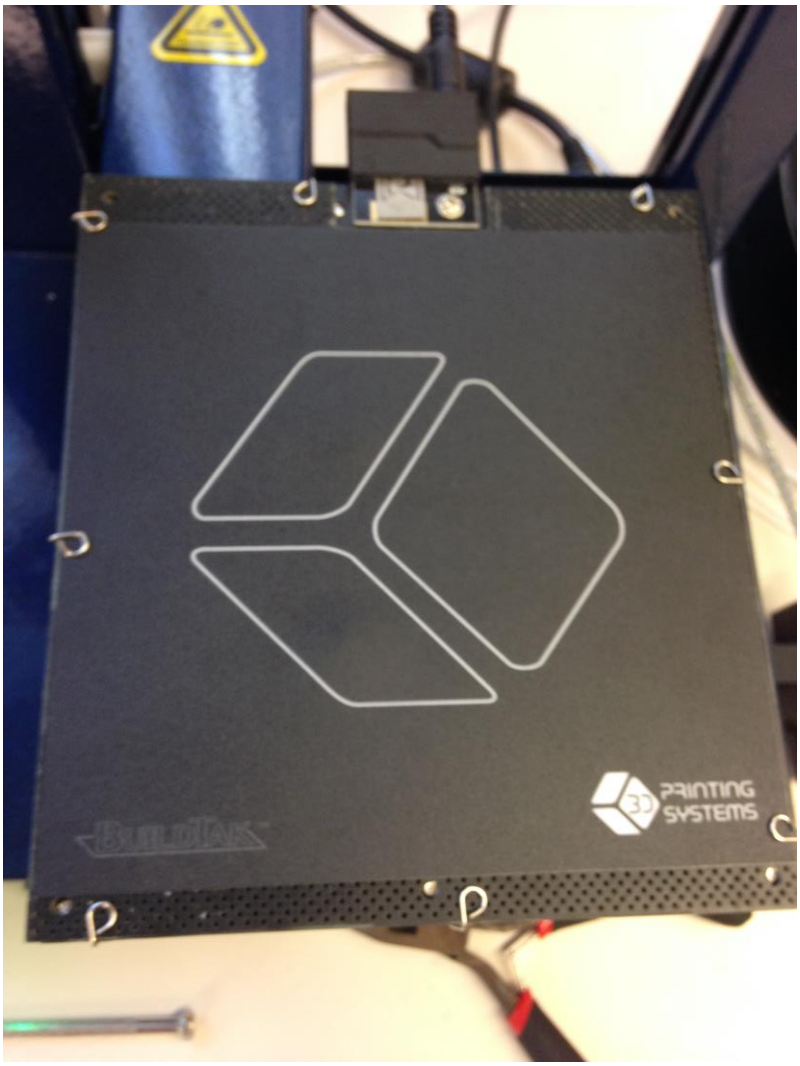

Figure 66: BuildTak sheet install on perboard.

- Carefully remove the model from the perboard using the spatula. The model didn't required too much force to remove it and when using the BuildTak is even easier.
- The final piece should be a solid, flexible and clear color model as shown in Figure 67. It will have good bonding between layers and high elasticity with excellent abrasion resistance.

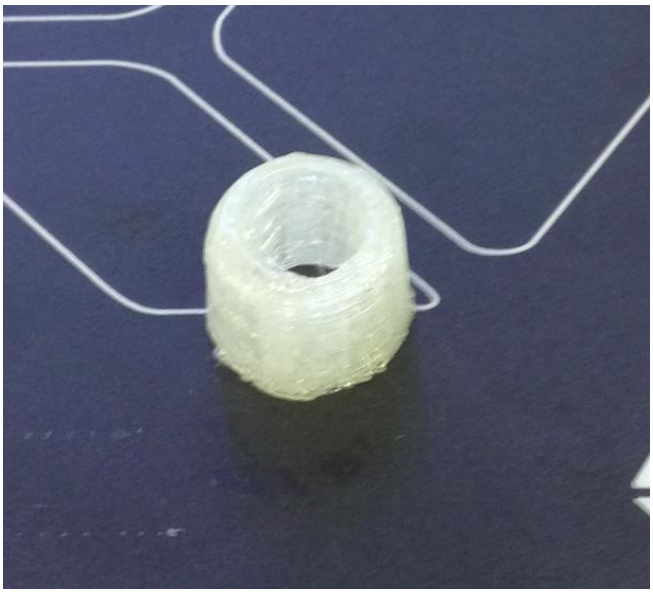

Figure 67: Successful bump stopper printed on TPE

4.7. Single Print

3D printing has many potential benefits as previously explained. For example, it allows printing intricate geometries and complex features in just one click of a button. The products and components can be designed specifically to avoid assembly requirements, hence eliminating labor and costs associated with the assembly processes. Common manufacturing of shock absorbers requires different components that are then assembled, as previously shown, but with 3D printing it can be done in one single piece. In order to explore this benefit the previously design shock absorber was printed in one single print.

First, all of the components were assembled in SolidWorks and then saved as one STL file. Like most desktop 3D printers, the Up Plus 2 has the limitation of printing size, which means the model can't be bigger than the printing platform size. The Up software revealed that the original design was too big to fit inside the platform, therefore the design had to be resized. Using the scale icon on the Up software the design was scaled to 0.7 of its original size. This allowed for the shock absorber to fit inside the platform and proceed with the printing.

The print of the shock absorber in a single piece was not as easy as one click of a button, it did require some adjustments. Since the model is complex and its original design was to be assembled, it had some difficulties. The orientation and the printing preferences were the main

factors for the print to be successful or not. After some tests the shock absorber was successfully 3D printed in just one piece as shown in Figure 68.

Figure 68: Single printed shock absorber

When printed horizontal the support material inside the cylinder prevent the piston from moving, therefore it was printed vertically with normal quality, 0.25mm Z resolution, and a semi solid fill. In order to get as less support material possible the support preferences had to be set to 5 layers dense and the area to 20 mm2. The extruder vent door was halfway opened to reduce the boding strength between layers, therefore making it easier to remove the support material after printing. The model came out with all of its patterns and features, but had a lot of support material as seen in Figure 69, that had to be carefully and patiently removed before being tested. After removing the support material the shock absorber was able to compress and act as a

functional shock absorber that could be used in toys or personalized products according to individual needs and requirements.

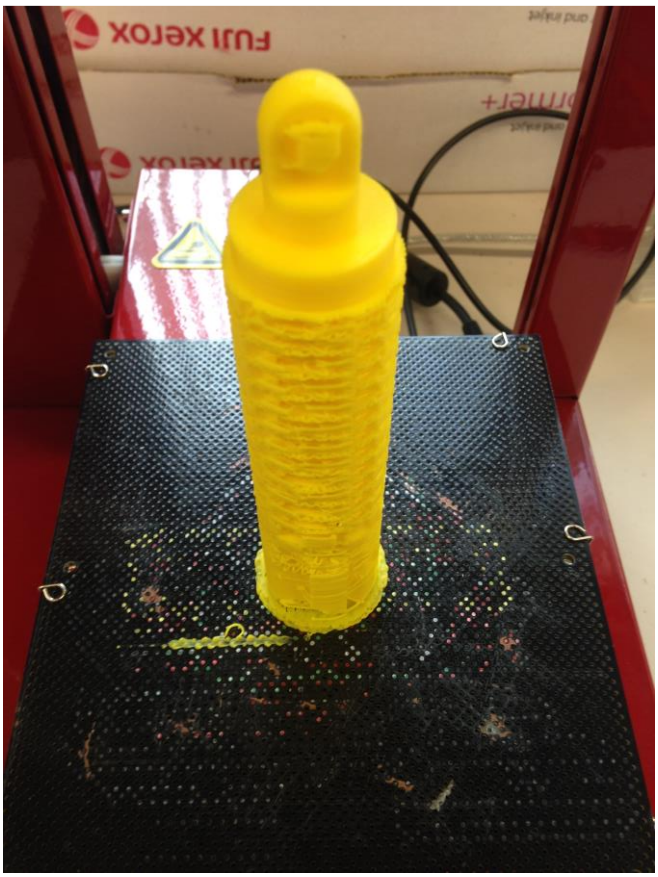

Figure 69: Single print shock absorber with support material

The total material used was 31.5 grams of ABS and the printing time was 2 hours and 12 minutes. These show a quick, accurate and low price prototype or end product that reduced costs of assembly. It also reduces the costs of tools production in the product development stage. The downside is with complex designs the support material is always needed, which requires time and patience to remove it, hence this could cost the same as the assembly costs.

5. Chapter 5 Tests and Results

5.4. Spring Rate

Another advantage of 3D printing is that by changing the filling less material will be used, therefore reducing costs and making components more efficient and lighter. The filling can also affect how the component works and behaves. A test was carried out with two helical springs with different fills in order to analyze the effect it has on the spring stiffness. The first spring was printed with a solid fill with white ABS, and the second with a semi-hollow fill in yellow ABS as shown in Figure 70.

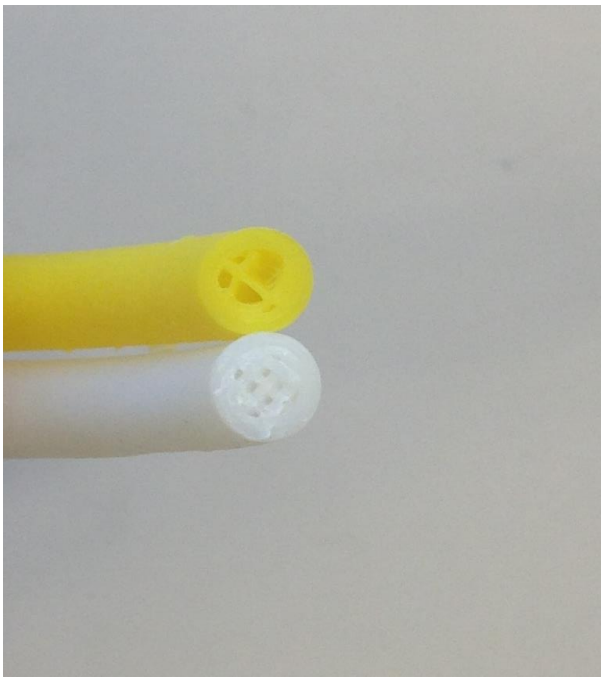

Figure 70: Interior fill of springs.

The two springs were compressed to almost the minimum load length with a couple of weights on top. A base with a tube was 3D printed in order to keep the spring on place while the weight was applied, and also to avoid the spring from buckling. Using a precision scale the total weight applied was of 350 grams and then using a Vernier caliper the compress length was measure as shown in Figure 71.

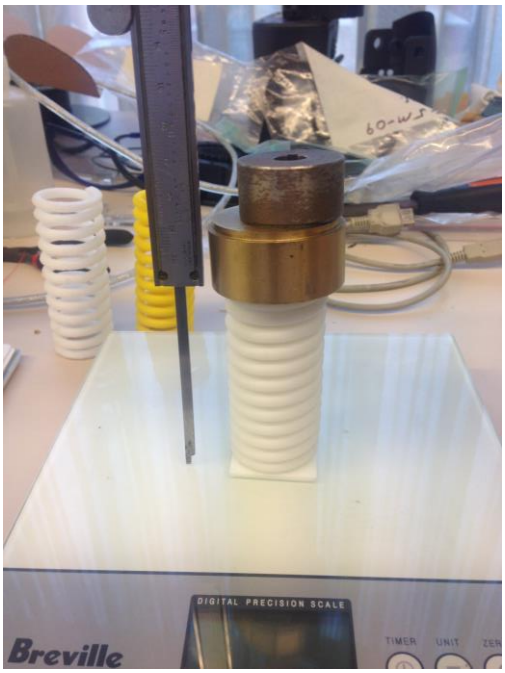

Figure 71: Spring rate measurement.

Applying the same force to both springs, the semi-solid spring compressed 3.2mm more than the solid fill. With the result and the specifications of the springs from table 4 the spring rate of each spring was calculated. The spring rate or stiffness is defined as the load required per unit deflection of the spring (Bhandari, 2007). The solid honeycomb is made of nearly solid plastic which made it stronger than the semi-solid, consequently it changed the density of the component, therefore having a higher spring rate or stiffness as shown in The 3D printed spring it's not entire a solid and therefore the modules of rigidity is also smaller if compared to solid ABS material.

Table 5 shows that if the same spring was made of stainless steel it will be 264 times stiffer with a spring rate of 44 kN/m.

With the spring almost to its minimum compress length the module of rigidity of the ABS could be also defined with the equation below and the data from Table 4. The module of rigidity or Shear Modulus is the coefficient of elasticity for a shearing force. It is defined as the ratio of shear stress to the displacement per unit sample length or shear strain (Norton, 2000).

$$G = \frac{k8C^3Na}{d}$$

The module of rigidity for the ABS in this case is 46.7 x 10^7 N/m^2 which is around ten thousand times smaller than the module of rigidity of steel that's 77GPa. The 3D printed spring it's not entire a solid and therefore the modules of rigidity is also smaller if compared to solid ABS material.

Table 5: Stiffness of the springs

Spring Rate or Stiffness		
Spring	A	B
Material	ABS white	ABS yellow
Honeycomb Filled	Solid	Semi-solid
Length (mm)	90	90
Weight (gr)	350	350
Force (N)	3.43	3.43
Compress length (mm)	72.6	69.4
Delta length ΔL (mm)	17.4	20.6
Stiffness k (N/m)	197.1	166.5

5.5. Costs and Time

An important variable to consider when manufacturing any component is the price and time it takes to build it.

Table 7 shows the settings, time and cost for each of the components that where 3D printed for the shock absorber. Most of the components where printed with a 0.20mm layer resolution and fine speed, in order to have a better surface finishing and quality, although it required longer times to print. Also, the fill used is semi-solid and solid in order to have strong components. The results show a total time of 6 hours and 53 minutes to 3D print the shock absorber with 83.1 grams of material used. This results show a quick way to manufacture the component and the time and amount of material can be reduced by modifying the layer resolution, speed and fill of each component. Although, before changing these variables the component must be analyzed depending on its final use because it will have a significant effect. Some components were printed at the same time for example the locking ring and the preload adjuster put this didn't

affect the time or material being used. Printing component together will reduce time of setting up and after printing times put the material used and the time it takes will be the same. The only way to reduce these times is by using two printers at the same time or using a faster printer.

The total cost of the shock absorber considering only the costs of material will be 7 AUD. The price for the materials is given in Table 6, which shows the price of 8 cents per gram of ABS and 11 cents for TPE. This means ABS is cheaper than TPE, also the materials that were used are not expensive and will get even cheaper with time. The prices were taken from 3dsystems.com.

Table 6: Price of ABS and TPE

Cost of Material			
Type	Mass (g)	Price (AUD)	Price per g (AUD)
ABS	700	59	0.084
TPE	500	58.7	0.117

Table 7: Cost, time and setting of each component

Component	**Layer Resolution (mm)**	**Speed**	**Fill**	**Time (min)**	**Material**	**Mass (g)**	**Cost (AUD)**
Spring	0.25	Fine	Semi-solid	166	ABS	29.4	2.48
Cylinder	0.20	Fine	Semi-solid	2	ABS	17.2	1.45
Locking Ring	0.20	Fine	Solid	19	ABS	3.2	0.27
Preload Adjuster	0.20	Fine	Solid	26	ABS	4.6	0.39
Piston with rod	0.20	Normal	Solid	44	ABS	6.6	0.56
Upper Cap	0.20	Fine	Semi-solid	54	ABS	8.1	0.68
Bottom Cap	0.20	Fine	Semi-solid	73	ABS	11.6	0.98
Bump Stopper	0.25	Normal	Semi-hollow	7	TPE	2	0.23
Seal	0.25	Normal	Semi-hollow	1	TPE	0.4	0.05
Total				**392**		**83.1**	**7.08**

5.6. Surface Treatment

One important process in manufacturing is the surface treatment where different industrial processes are used to alter the piece surface in order to obtain a certain property. After a surface treatment the object can improve in appearance, adhesion, reflection, solder ability, tarnish resistance, corrosion resistance, chemical resistance, friction and wear, change conductivity, and

remove surface flaws (Ebnesajjad and Ebnesajjad, 2006). Overall, this process will improve the functions and or service life of the material.

In 3D printing when a model is printed in ABS material it can be given a smooth, shiny surface with an acetone vapor bath. This happens because the acetone breaks the secondary bonds between the ABS polymer chains, and as a result softens the outer layer of the plastic. The chains move to a more stable position by sliding past each other and closing the gaps between each layer. The surface tension in the liquid-like plastic layer polish the surface texture and after the acetone evaporates the plastic returns to its original hardness (Chapman et al., 2014). If the process is done correctly as shown below it will ensure a very consistent surface.

5.6.1. Process

- Make sure to do it on a well-ventilated area or use an extractor.
- Add a small amount of acetone into a glass jar around 3 mm deep.
- Take the glass jar to a heated platform and heat it up until a vapor cloud can be seen coming up the jar.
- Lower the temperature to a medium heat.
- Using a fishing line or a cord lower the model into the jar.
- Have the model suspend inside the jar without touching the walls.
- Close the jar using a lid or aluminum foil, to speed up the process and reduce acetone vapor in the working environment.
- The object will turn shiny and smooth in a few seconds, depending on the temperature that is being used the process can take longer or less time.
- When you are satisfied with the amount of smoothing, carefully retract the object from the jar and hang the part up to dry.
- Remove the jar from the heat and leave it closed until the vapor cools and condenses back into liquid to be store again in the acetone container.
- Allow the part to dry for around one hour without touching it.

The helical spring was given a smooth, shiny surface finish by immersing it in the acetone vapor bath as shown in Figure 72. The spring was immersed in the jar for 3 minutes and then removed when the model was shiny and smooth. It also ends up with a well-bonded and continuous layer on the outer surface as seen in Figure 73. Depending on the acetone temperature the process can

be faster, but be careful not to leave it inside for too long. If the piece is left for too long blister-like bubbles will appear on the model surface. This method resulted to be very effective and fast, although safety precautions must be taken in account since acetone is flammable and it shouldn't be inhaled. The boiling point of acetone is 56°C but it will evaporate at room temperature therefore this method will also work without heating up the acetone, although it will take much longer time (Sink, 2014).

Figure 72: Acetone vapor bath

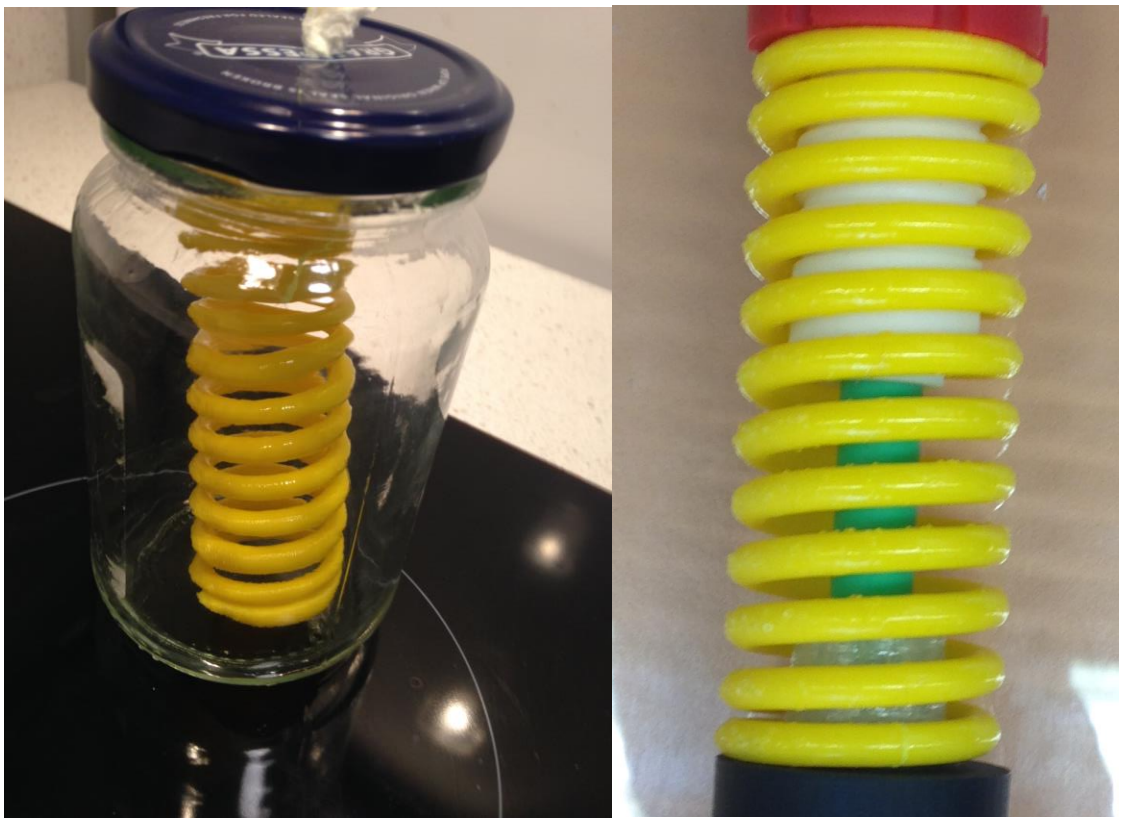

Figure 73: Spring after surface treatment

The conclusion reached in a recent study (Chapman et al., 2014) was that "treating the 3D printed samples with acetone vapor gave them a smooth surface finish and increased the toughness by 50% to 100% with only slight losses in tensile strength". The surface treatment overall rises the average tensile strain, and reduces by a small amount the average tensile stress. This occurs due to the fact that it fuses the multiple strips of ABS on the edges of the dogbone as shown in Figure 74 and Figure 75. In Figure 74 the texture of the surface leads to stress concentration, whereas in Figure 75 the acetone treatment changes it to a smooth surface with uniform bonded layer of filament. Hence, the smooth surface gives an increase in maximum elongation and decrease in maximum strength (Chapman et al., 2014).

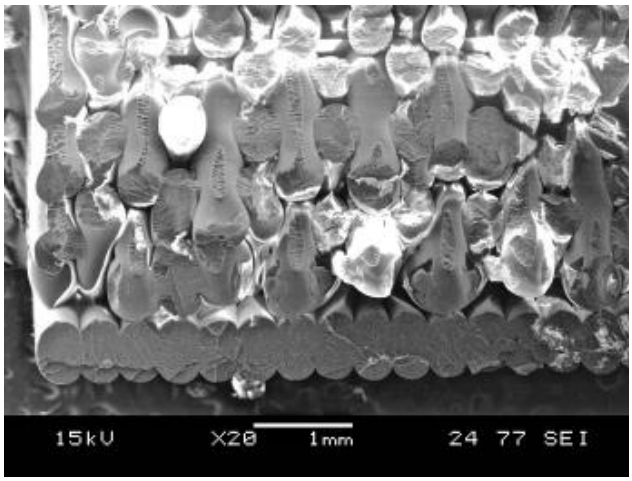

Figure 74: SEM image of 3D printed fracture surface with no acetone vapor treatment (Chapman et al., 2014).

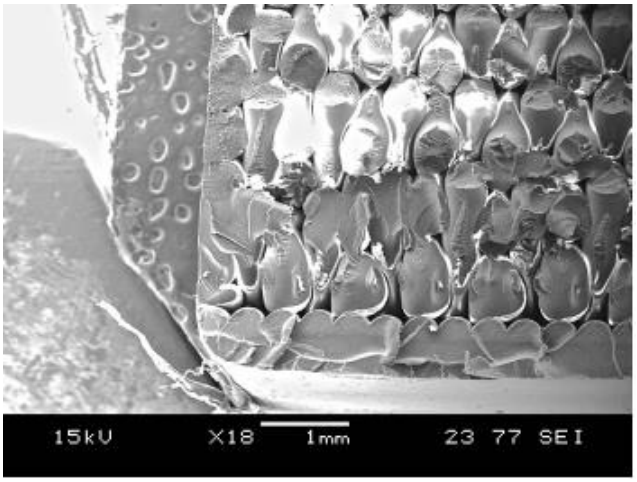

Figure 75: SEM image of 3D print fracture surface after acetone vapor treatment (Chapman et al., 2014)

The surface treatment with acetone vapor not only improves the model appearance but can also reduce times and costs which are a really important factors to consider when manufacturing. When the component's most important requirements are strain or toughness the 3D printing process can be faster by reducing the resolution and then doing an acetone vapor surface treatment.

5.7. Functionality

In order to test the functionality of the 3D printed shock absorber the bottom cap was switched with the flat-faced follower cap and then fixed to a cast acrylic sheet. Figure 76 shows the assembled shock absorber with the eccentric cam system in order to be tested. The shaft of the eccentric cam was connected to the electric drill and the speed was gradually increased. The shock absorber worked as expected, it compressed 15mm on each cycle and then returned to its original shape. The ABS material with the acetone bath worked excellent as a spring because it didn't even fail at the highest drill speed. It was successfully tested for 5 minutes at different speeds without inconveniences or any signs of failure.

Figure 76: Assembled shock absorber

The threads also work properly holding the assemble parts together at all time. The preload adjuster can easily be moved to adjust the spring stiffness. When it was moved clockwise the spring became tighter and therefore the shock absorber became stiffer.

In order to reduce the friction between the cylinder and the piston with the seal a bit of oil was used which helped for a smoother movement. The 3D printed shock absorber worked properly damping the force created by the movement of the eccentric cam, and dissipating the energy. Figure 77 shows the spring being compressed by the cam connected with the drill. The results showed that the 3D printed shock absorber functions properly and it could be used in any application where the force applied is not bigger than 3.47 Newton's.

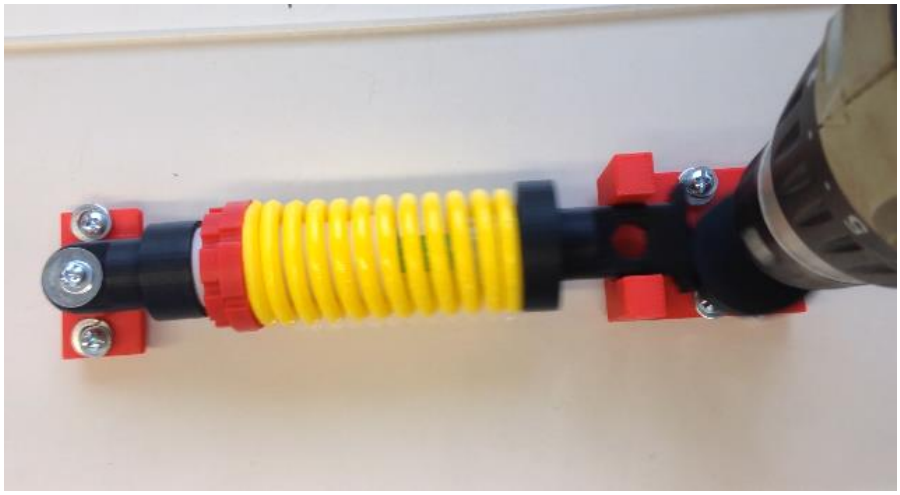

Figure 77: Functional shock absorber

6. Chapter 6 Summary and Conclusions

3D Printing is a relatively new manufacture technology that was primarily used for prototyping, until nowadays that has evolved to the point of being able to create end products. It requires very little setup time since no molds or custom tools are needed. There are different Additive Manufacturing Technologies that build parts layer by layer but the most common one is Fused Deposition Modeling (FDM) technology, which was used on this project.

This thesis shows that with the right knowledge and understanding of this technology, functional parts can be printed using just a simple and inexpensive desktop 3D printer like the Up Plus 2. It was successfully able to print a functional shock absorber and showed how advanced and useful this manufacturing technology is. Following the steps and guidelines shown in this study the 1.75mm diameter filament was extruded and forced out through the 0.4mm diameter nozzle into the build platform. The nozzle followed a computer-controlled path for building up the part layer by layer. Therefore the final product was not a completely solid object but a matrix of fused filaments. The Up Plus 2 printer is a desktop plug and use 3D printer that clearly shows how valuable and innovative this technology is. Although, when it comes to printing complex and function parts it is not as simple as plug and use. As shown with the shock absorber it required a deep understanding of the system in order to modified preferences and settings to successfully print. The temperatures and any environmental changes during the printing have a significant effect on the result, for example a draft could warp the model. The adjustments of settings and preferences before printing are really useful as shown with the experiments, because it allows the user to improve the design, reduce costs and others. By changing the fill the printed model will be lighter, will take less time to print, and also safe material. This option can also be used to modify the performance of the object, for example changing the stiffness rate of the spring.

The cam system that was implemented to check the functionality of the shock absorber worked as planed and demonstrated that ABS material can also work as a flexible spring. The shock absorber functioned as expected with no issues so it can be used in any toy or application where it may be needed. The total cost for the shock absorber was 7 AUD and it took a total time of 392 minutes. This time is only the total printing time excluding the design, the set up, and post processes times. The print time is proportional to 3D volume and surface complexity. This

demonstrates the Up Plus 2 can build complex components in a relative short amount of time and the cost is not high for a single personalized component. The cost of the material for ABS is 0.8 cents and TPE 0.11 cents per gram, which is relatively high compared to some materials used in traditional manufacture. Although, those prices will continue to reduce as this technology keeps growing.

After the model is successfully printed a post processes can be done to improve the surface finish and properties. The acetone vapor bath is an efficient surface treatment for models printed on ABS. As shown with the 3D printed spring the acetone vapor gave it a smooth shiny surface with well bonded and continuous layer on the outer surface. Additionally, the acetone vapor improves the strain, toughness, and surface finish with only a small reduction in stiffness and tensile strength because of the melting and fusion of the ABS. Furthermore, it can also save time and money by reducing the 3D printing resolution and then doing the surface treatment, hence the acetone vapor bath is really useful and efficient.

The main disadvantages of this technology at the moment are the machine resolution and the materials available. However, many research and investigations are being carried out in order to develop better printers and new materials that will revolutionize the world. The material ability to print accurately and fuse fully determines if it's suitable for 3D printing or not. One of the newest materials TPE, which is a flexible rubber like material that can be used in numerous applications, was successfully printed in this research. This material allowed for a bumper stopper and a seal to properly function with the shock absorber. The biggest difficulty experimenting with this material was due to the fact that the Up Plus 2 software is not open source therefore, the extruder temperature couldn't be modified. I found this material to be very useful and fun to work with. If the right extruder temperature could be set it may retain its elasticity as well as increase it viscosity as it leaves the print head, allowing prints to be cleaner with less filament drag. Another limitation of this technology is the printing platform size because the object can't exceed that size. If the platform size is not a restriction the object can be printed on single piece to avoid assembly costs. Although, if the printed piece is complex like the shock absorber, it will probably take lots of time to remove the support material which can have the same costs of the assembly costs.

For further research the spring design could be printed in different materials. Printing the spring with different materials and then comparing to the ABS will be really interesting, for example with nylon. With different materials the specifications can be obtain and compare to see which one is more suitable for the shock absorber. As shown in the study the module of rigidity of the ABS is around ten-thousand times less than steel, and the spring will be 264 times stiffer if it was manufacture on stainless steel. Each material has its own recommended extruder temperature ranges, which are shown in this study, so I would recommend using an open source 3D printer to select the exact temperature needed. It will also be interest to try new post process like carbon fiber lamination, epoxy resin, and polyester resin to improve the strength of the printed objects.

The recommendations for any one working with 3D printing is to follow the guidelines provided with this research. Always read the 3D printer manual and know the specifications of the materials that you will be using. If a shock absorber is require I will recommend the basic twin-tube type because it will be faster and easier to 3D print. Furthermore, complex designs are more suitable for this technology especially if the convectional manufacturing processes are not able to manufacture or takes too much time. Also keep in mind the manufacturing price is fixed with this technology and does not fluctuate with mass production like traditional manufacturing methods. When using Additive Manufacturing is recommended to identify low volume and where redesign is needed.

In conclusion FDM technology is a powerful manufacture method that's continuously growing and improving at a fast rate. Although, it still has some limitations it proofed it can manufacture functional complex objects. It will not replace traditional manufactures methods in some time, but for now it's improving the overall manufacture. It allows redesign and building complex and personalized objects where traditional manufacture is inefficient. It's currently having a great impact on society and pretty soon it will change the way we live, therefore research and experiments should continue to be carried on this promising field. With the dramatic drop in prices and the increase in free 3D software, it is very likely that this field will be even more accessible within the next few years. 3D printing will bring manufacturing to non-manufacturers just like computers years ago.

7. Appendix

Shock Absorber Sketch Diagrams

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